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(54) **VARIABLE GEOMETRY TURBINE**

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See application file for complete search history.

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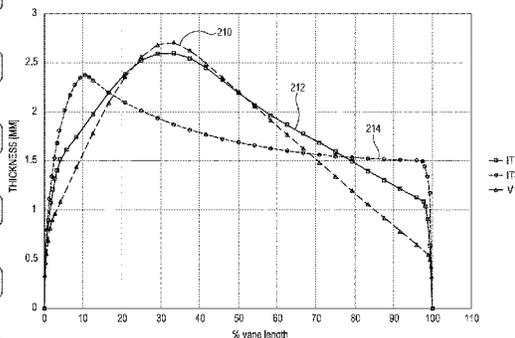
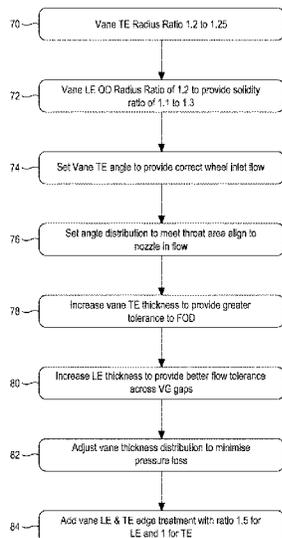
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(57) **ABSTRACT**

Variable geometry turbines having new configurations of vanes are disclosed. New methods for designing new configurations of vanes for geometry turbines having are also disclosed.

19 Claims, 15 Drawing Sheets



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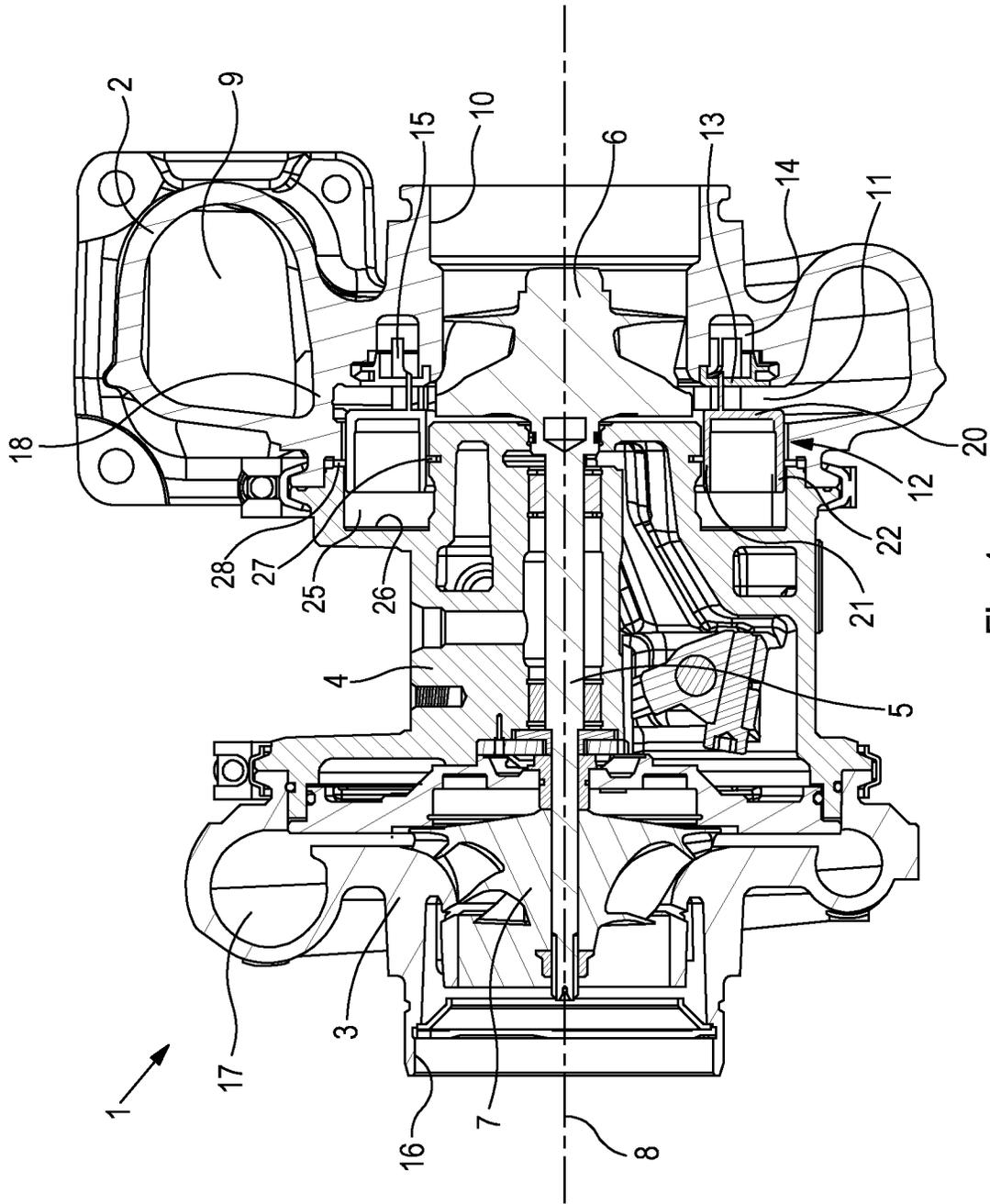


Fig. 1

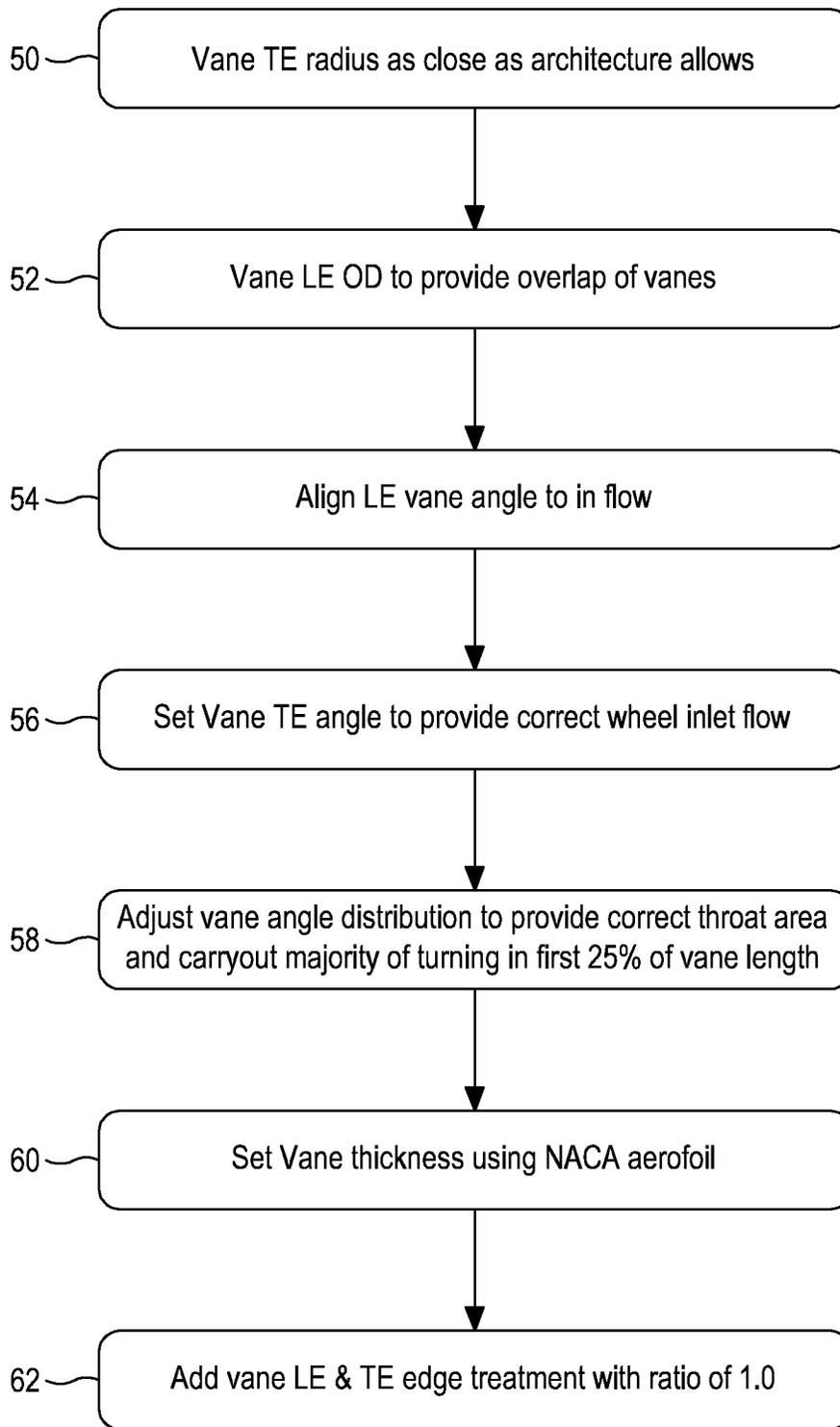


Fig. 2

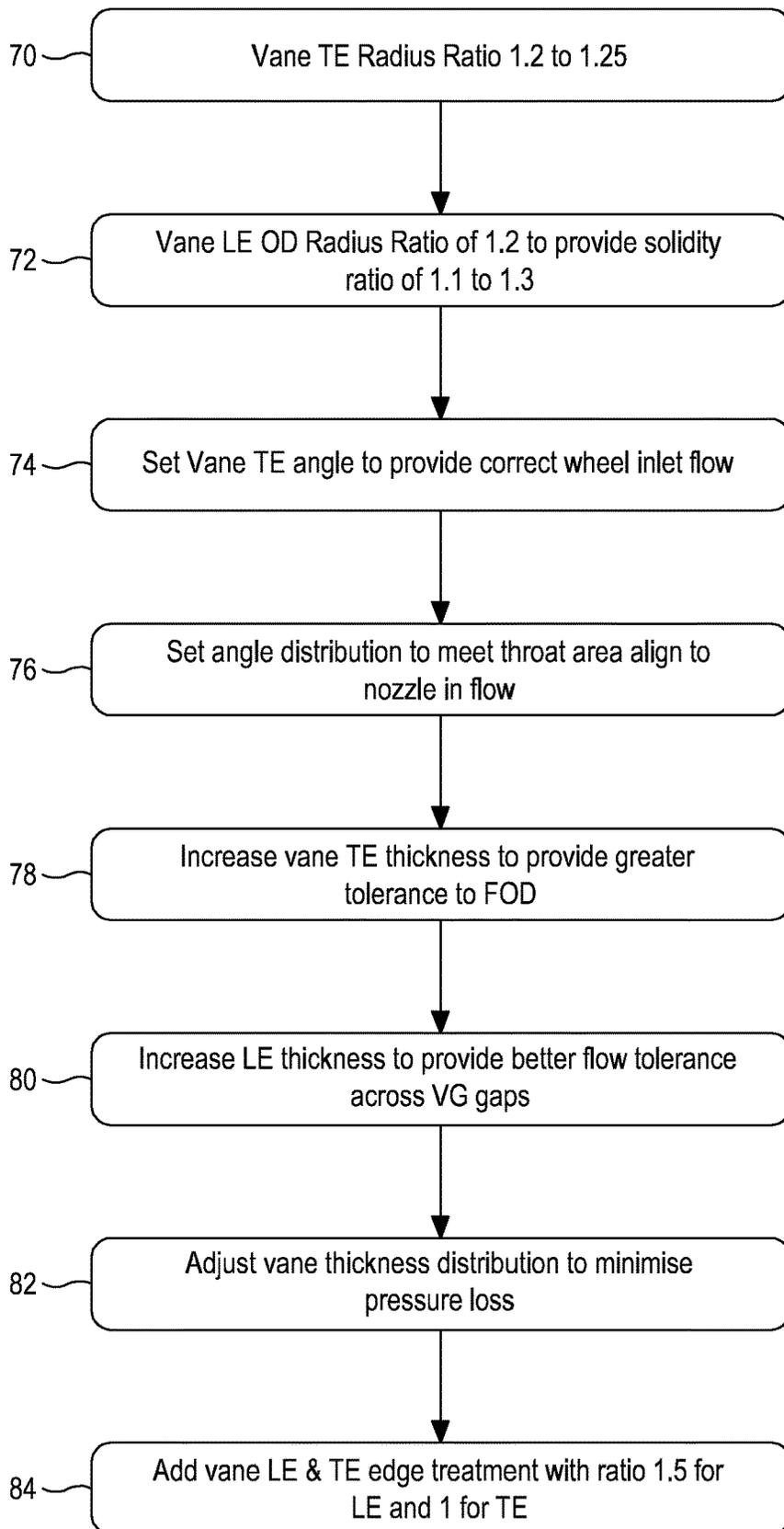


Fig. 3

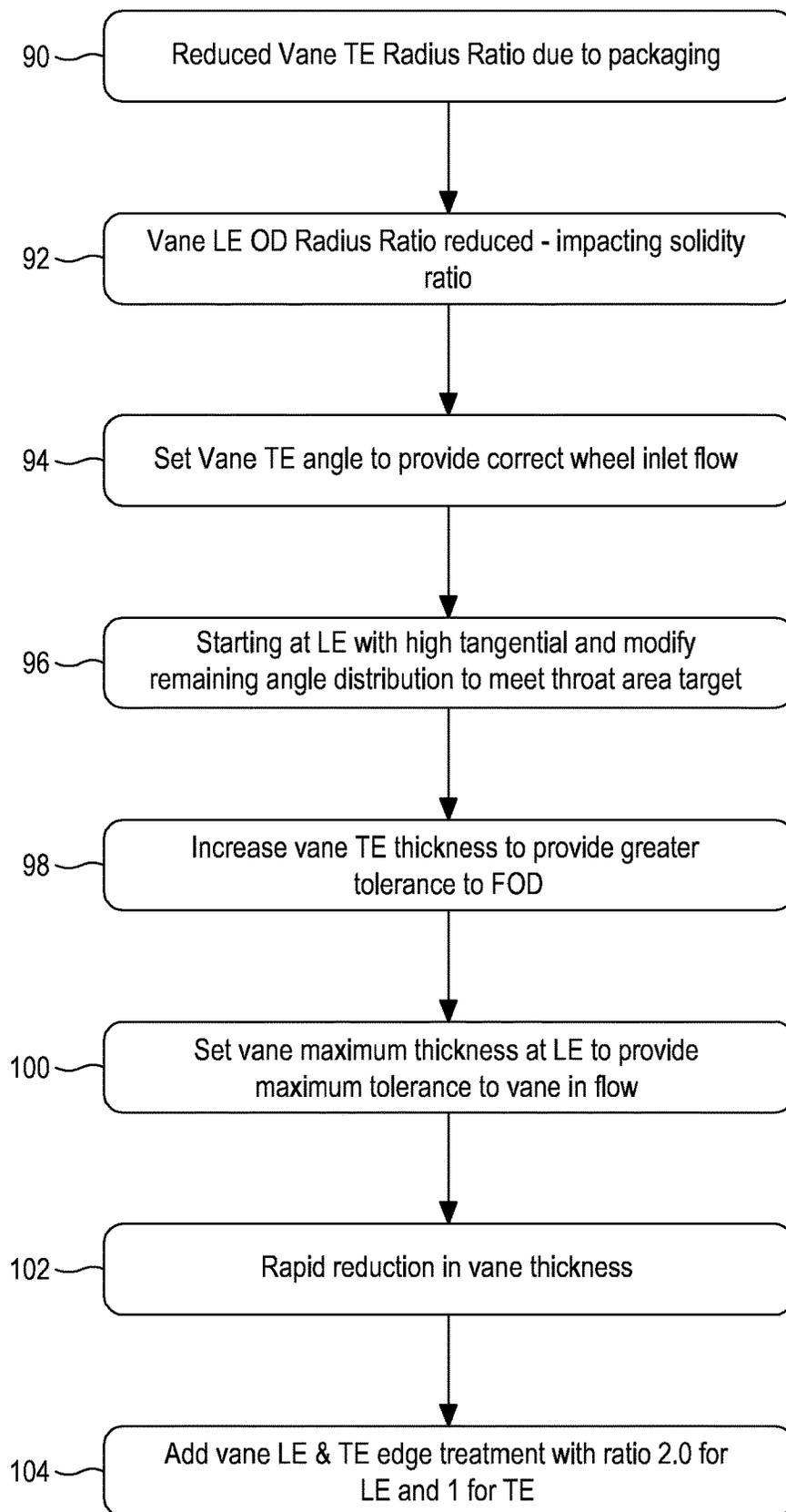


Fig. 4

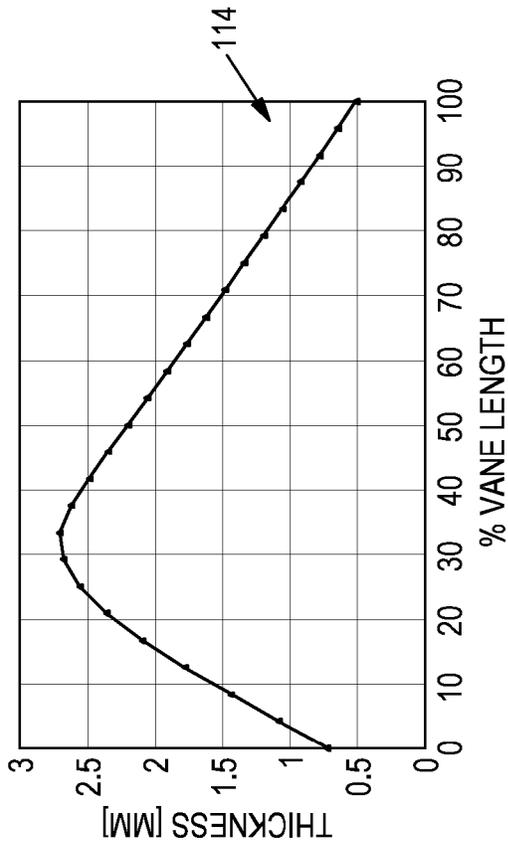


Fig. 5B

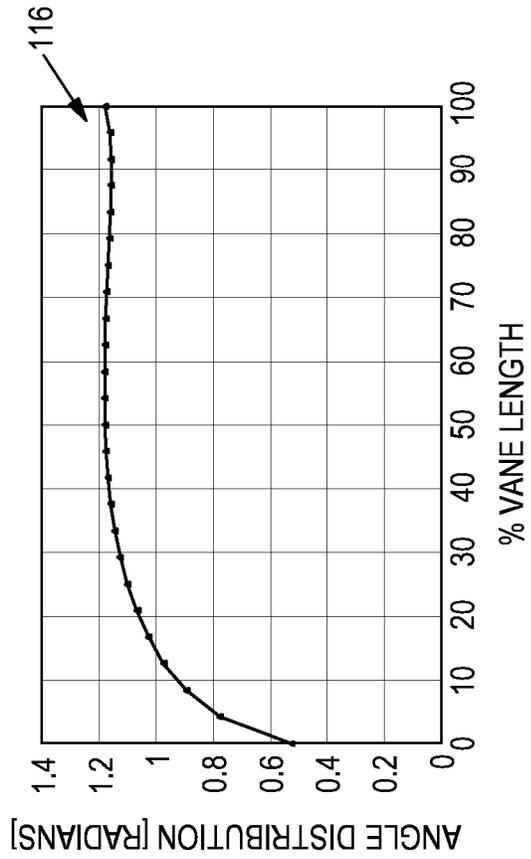


Fig. 5C

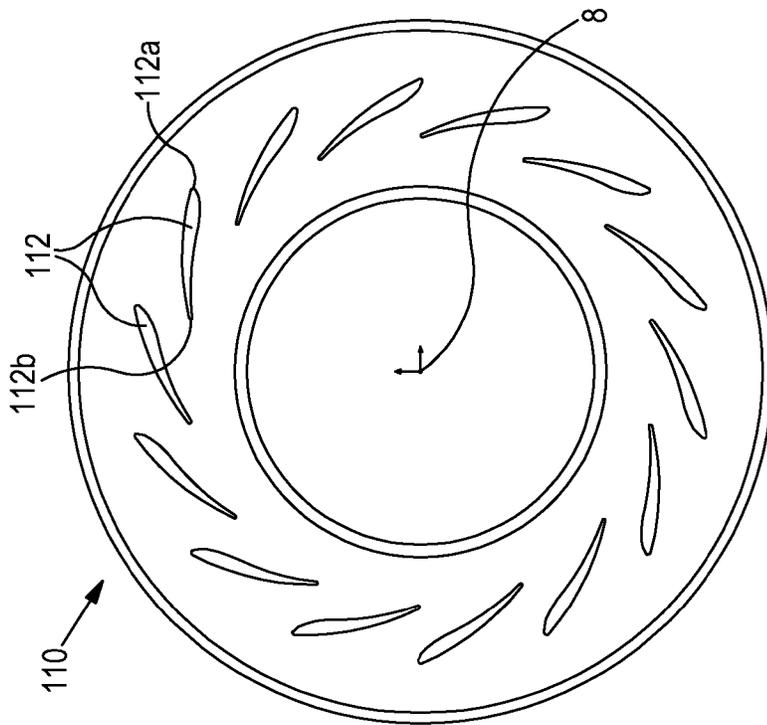


Fig. 5A

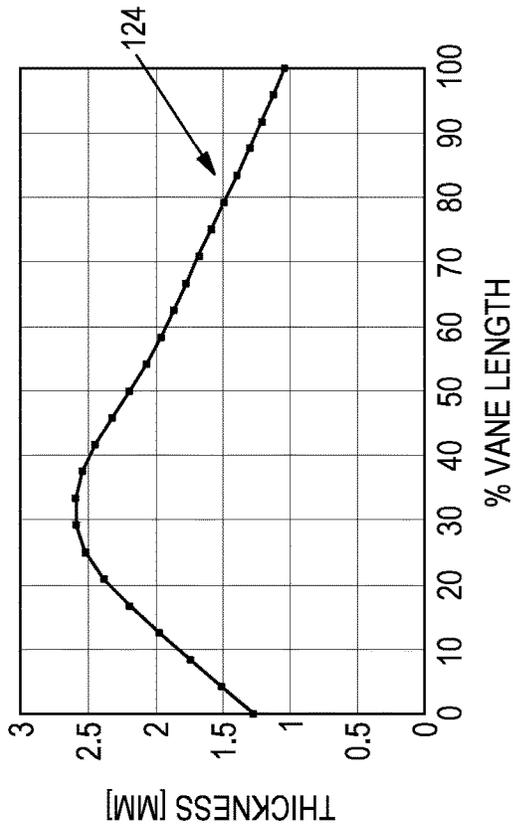


Fig. 6B

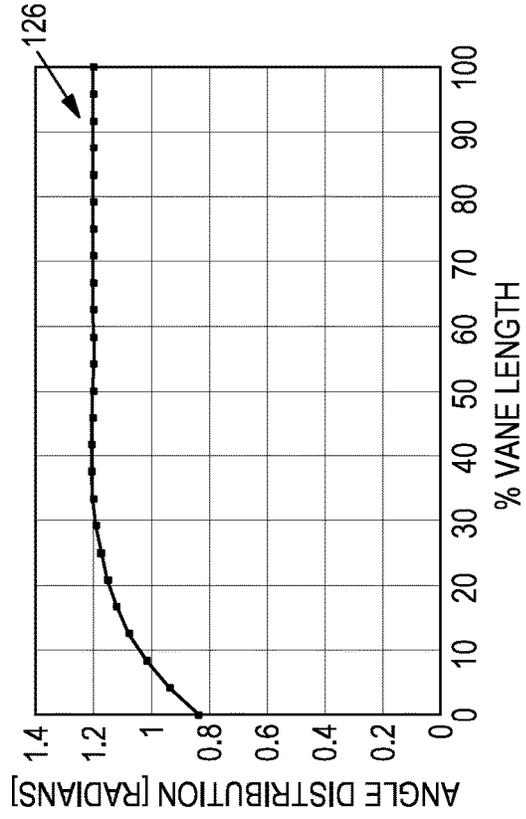


Fig. 6C

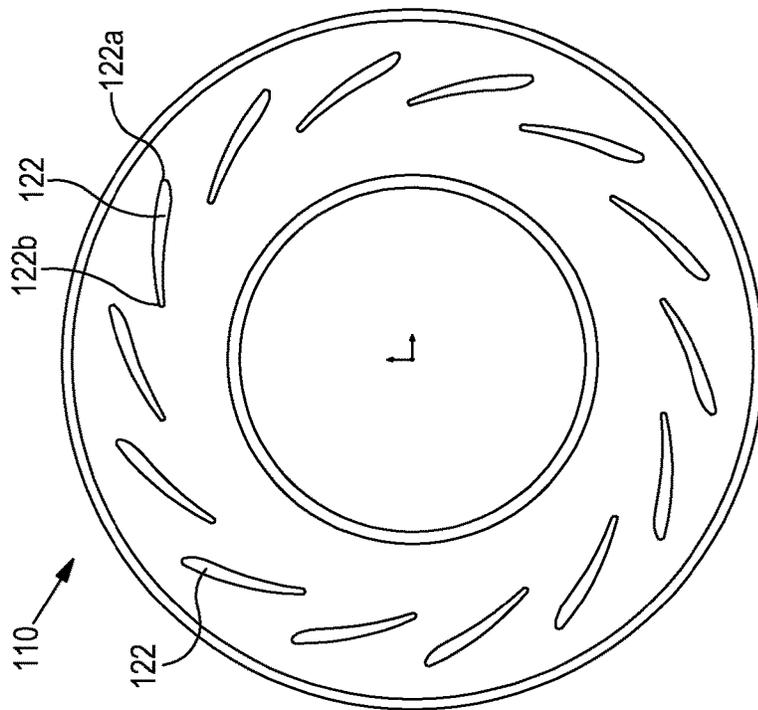


Fig. 6A

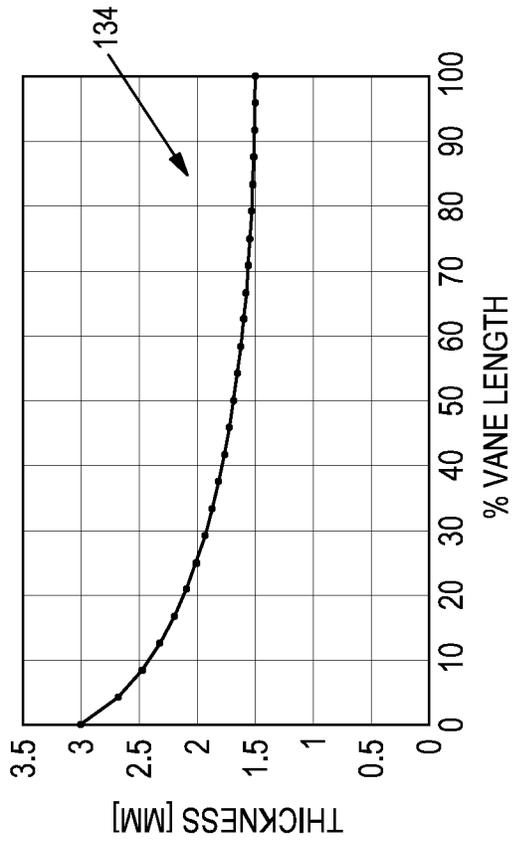


Fig. 7B

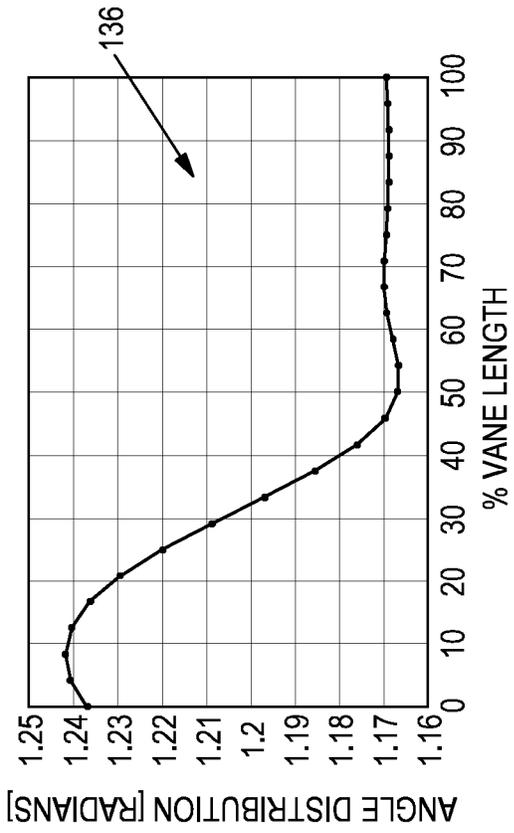


Fig. 7C

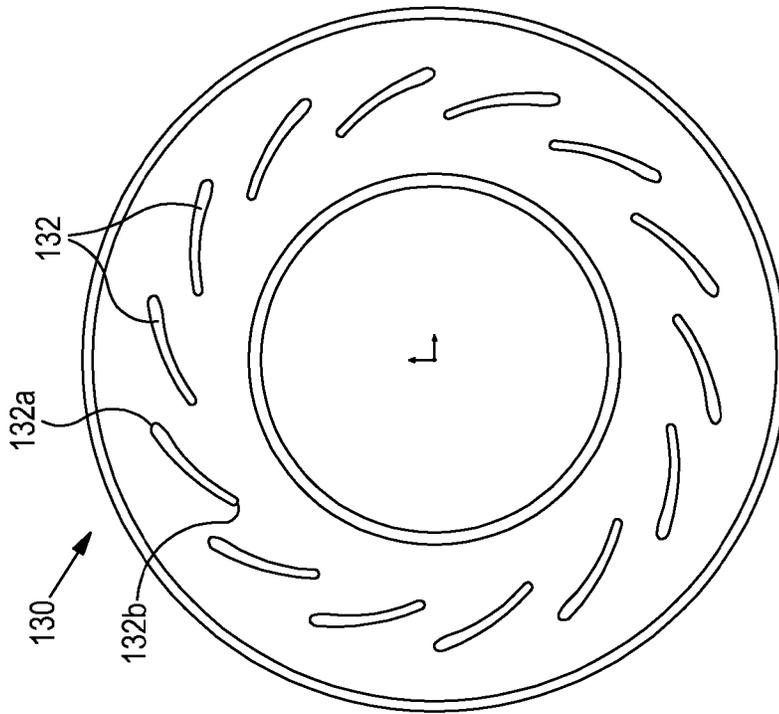


Fig. 7A

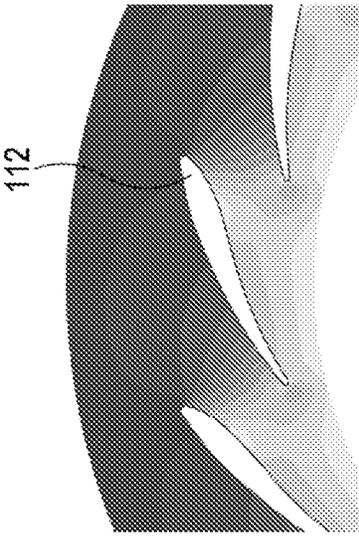


Fig. 8B

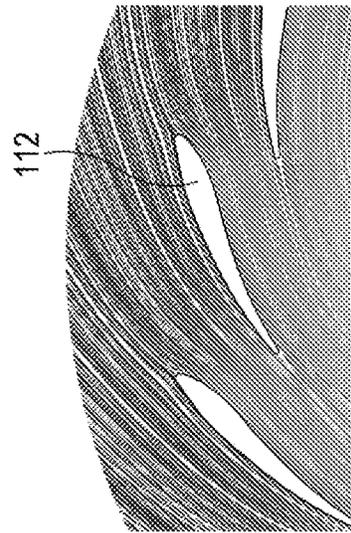


Fig. 8A

V14 (design)

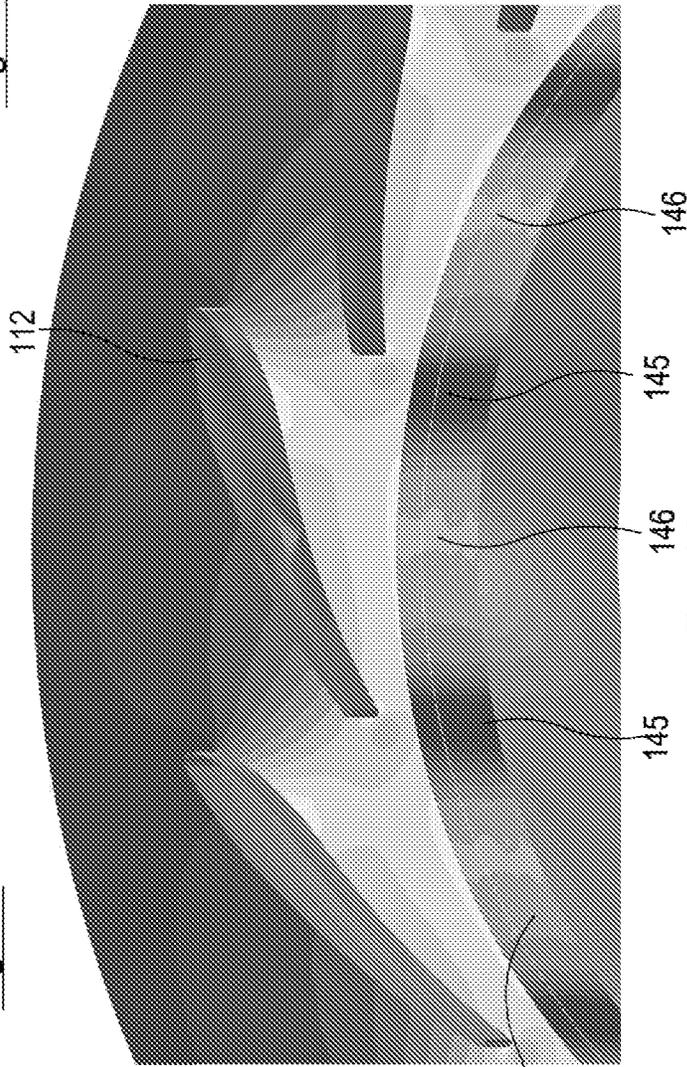
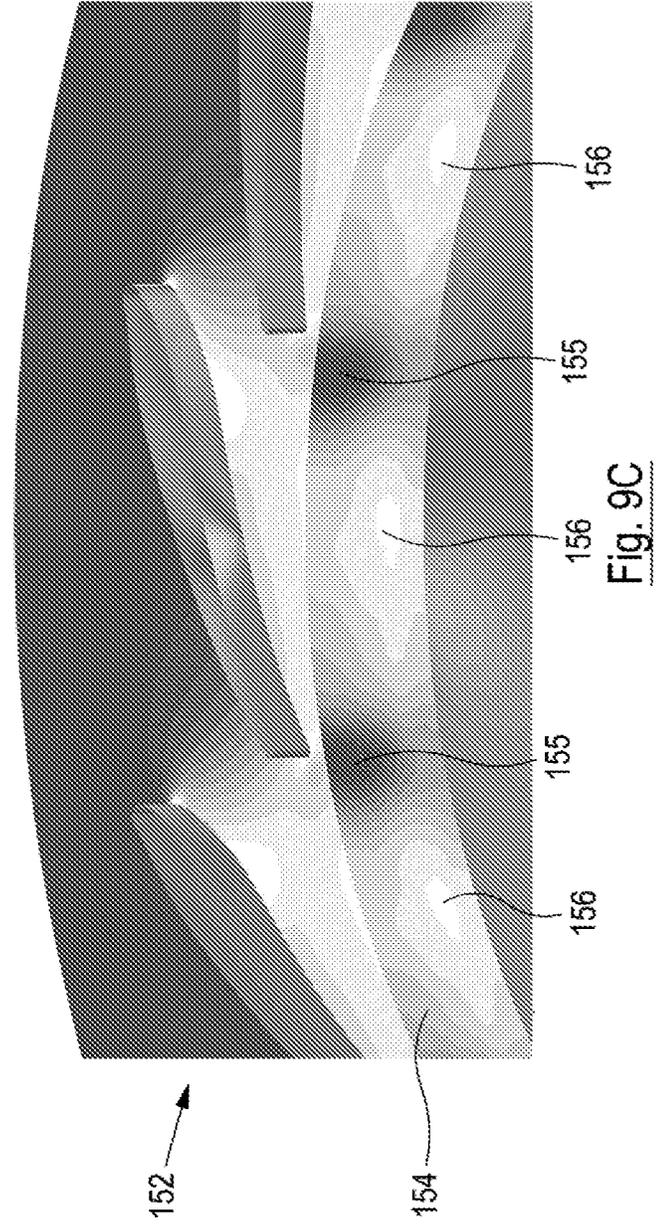
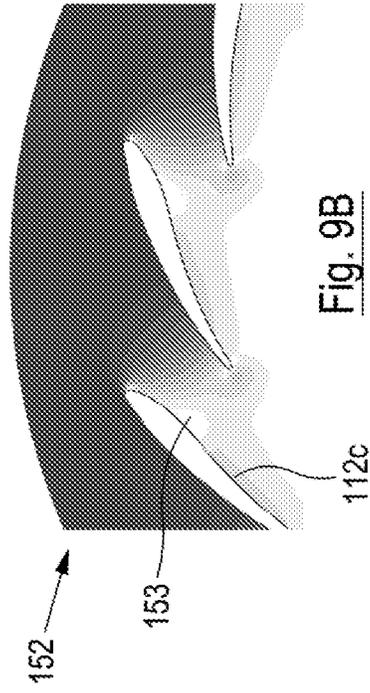
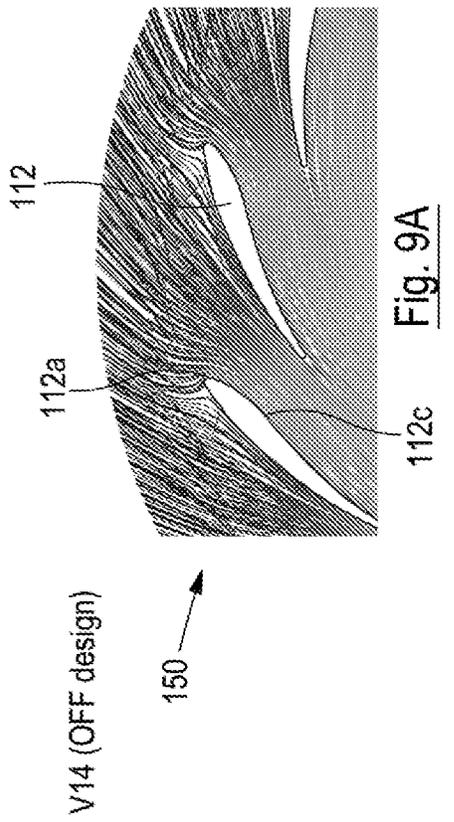


Fig. 8C



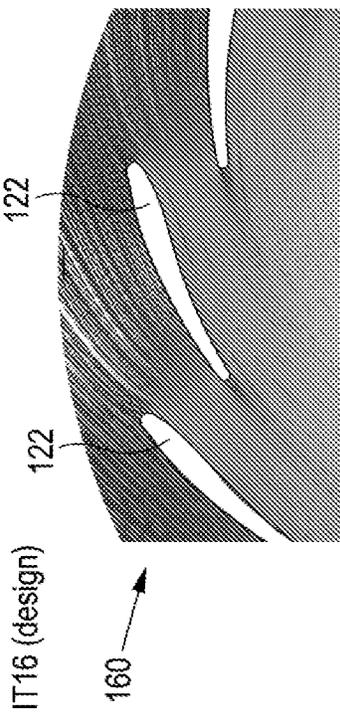


Fig. 10A

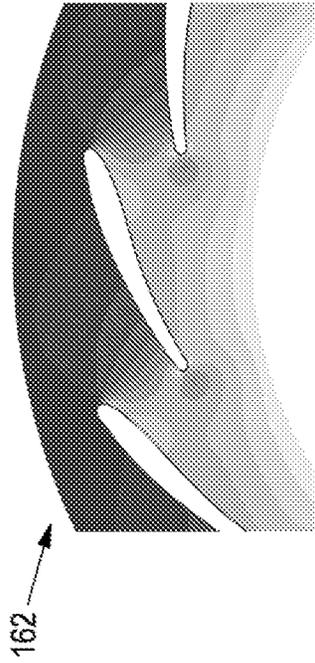


Fig. 10B

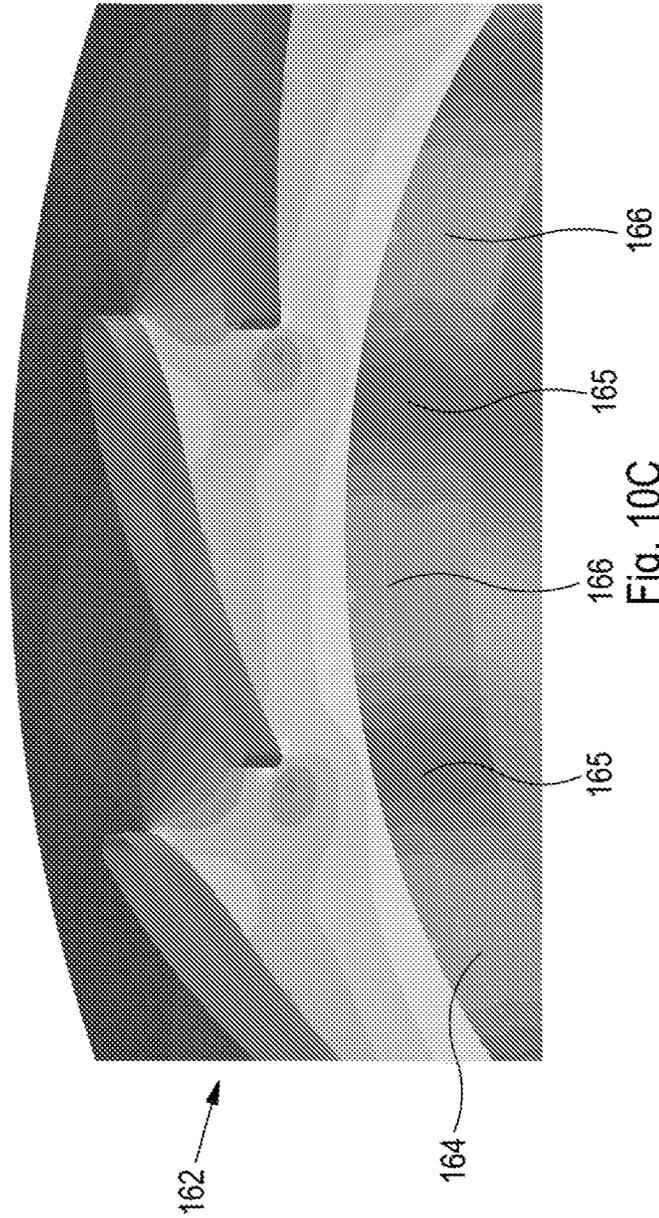


Fig. 10C

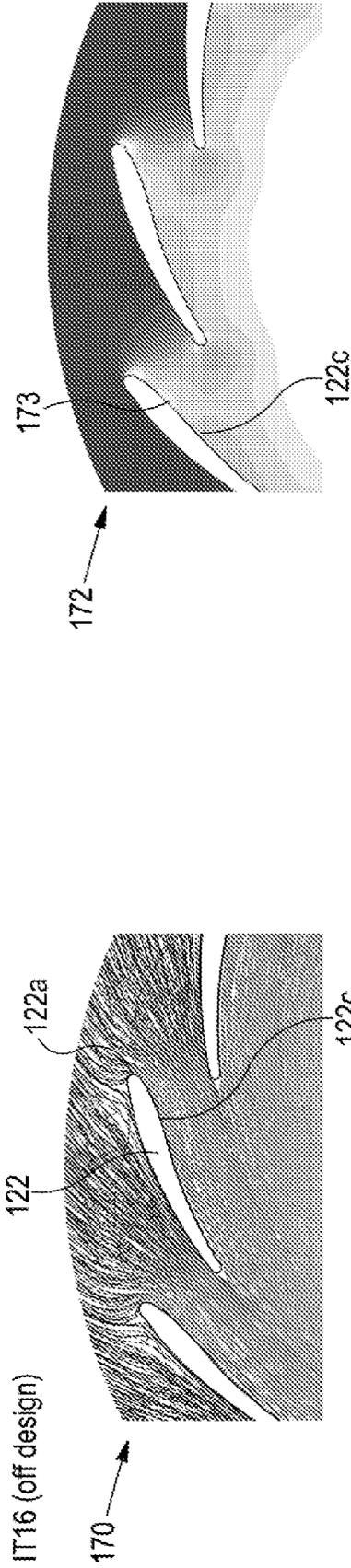


Fig. 11A

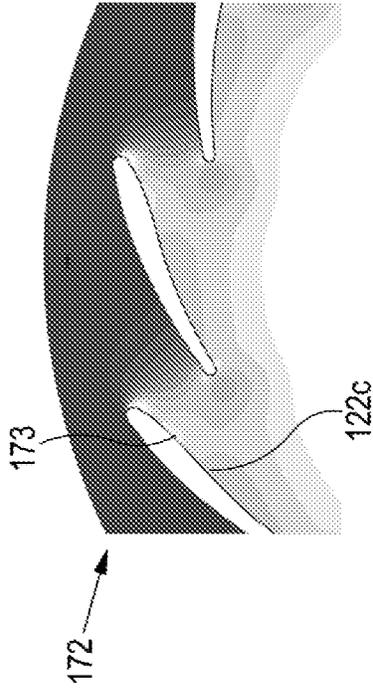


Fig. 11B

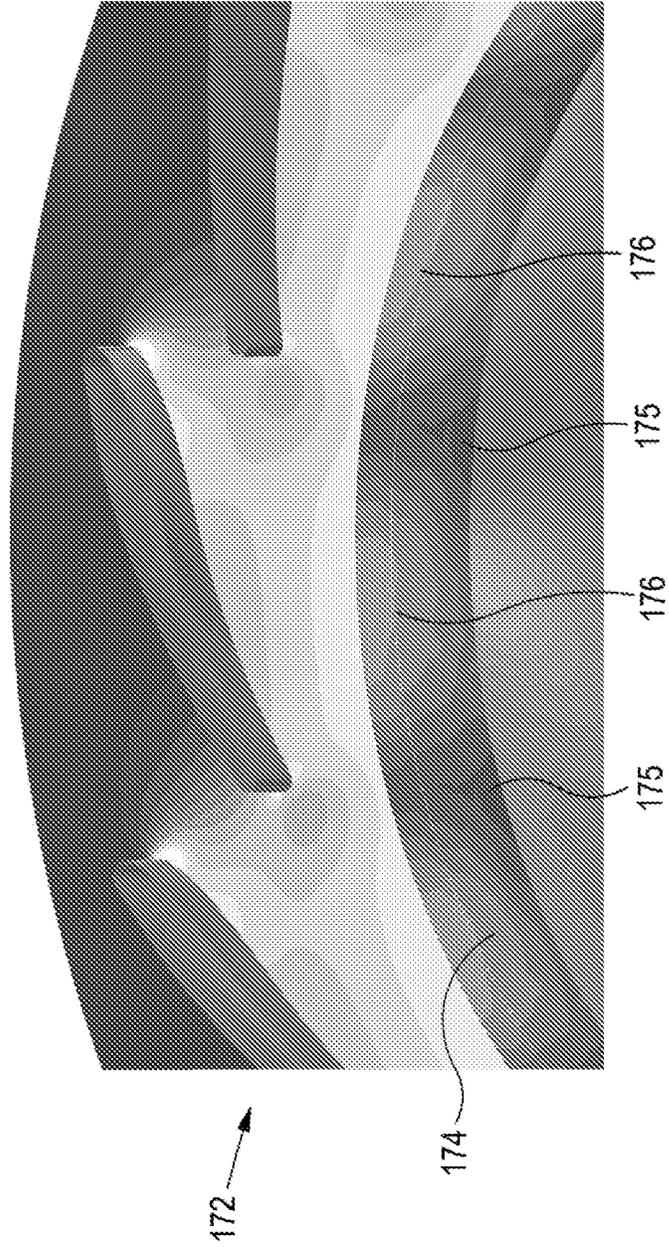


Fig. 11C

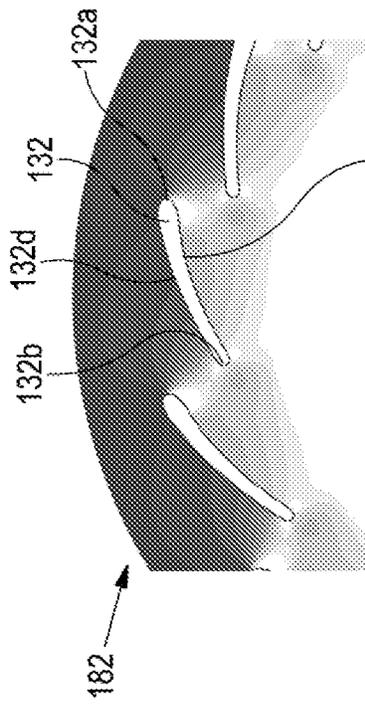


Fig. 12A

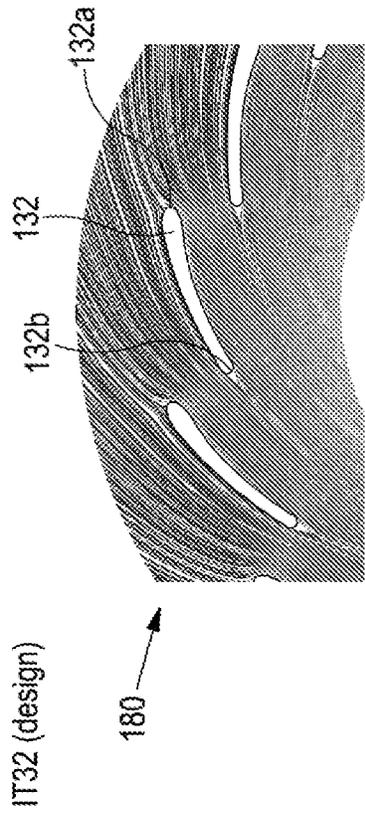


Fig. 12B

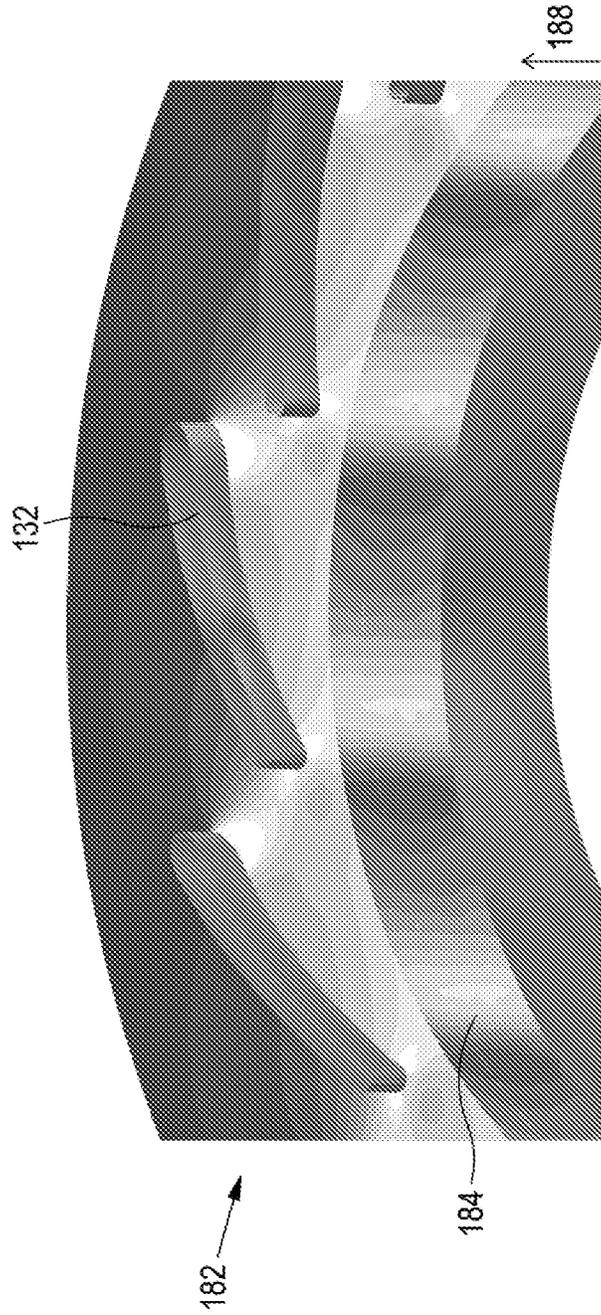
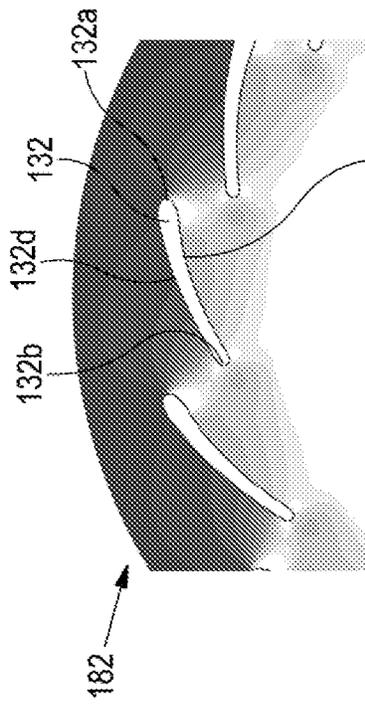


Fig. 12C

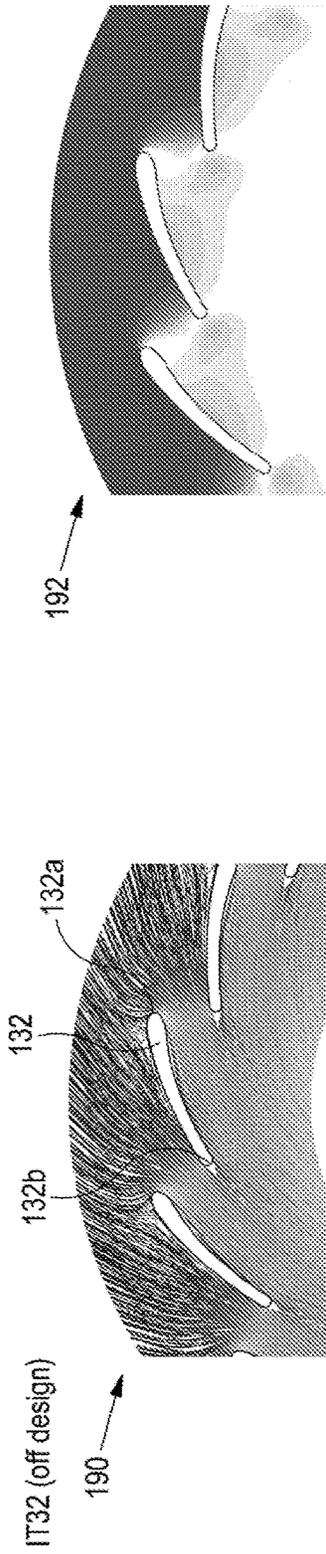


Fig. 13A

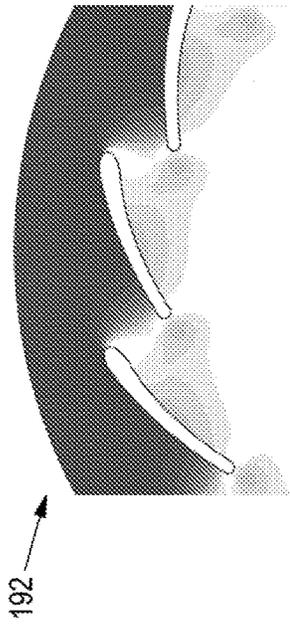


Fig. 13B

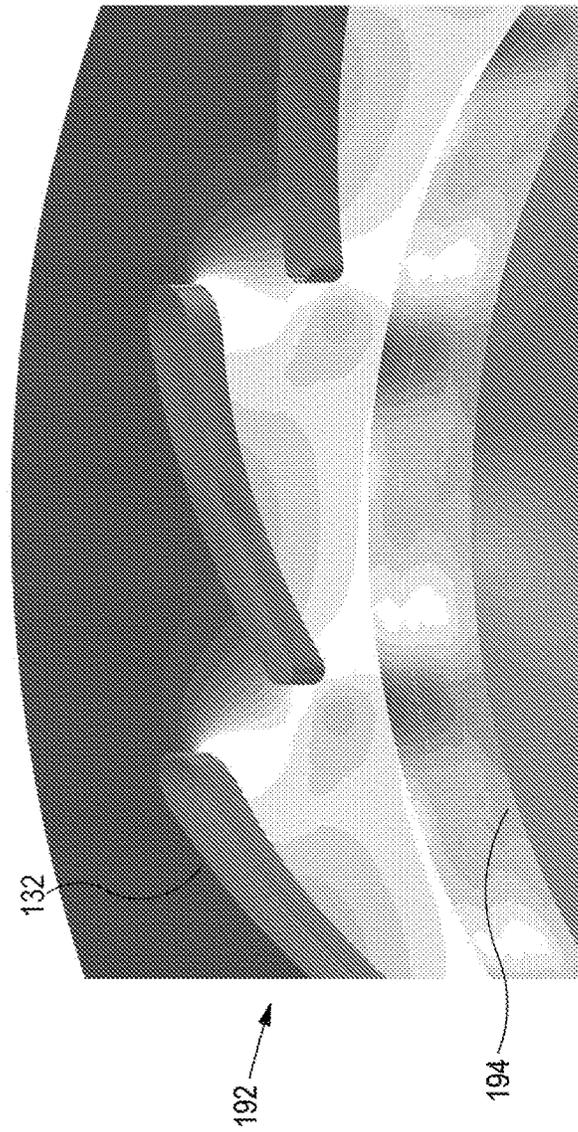


Fig. 13C

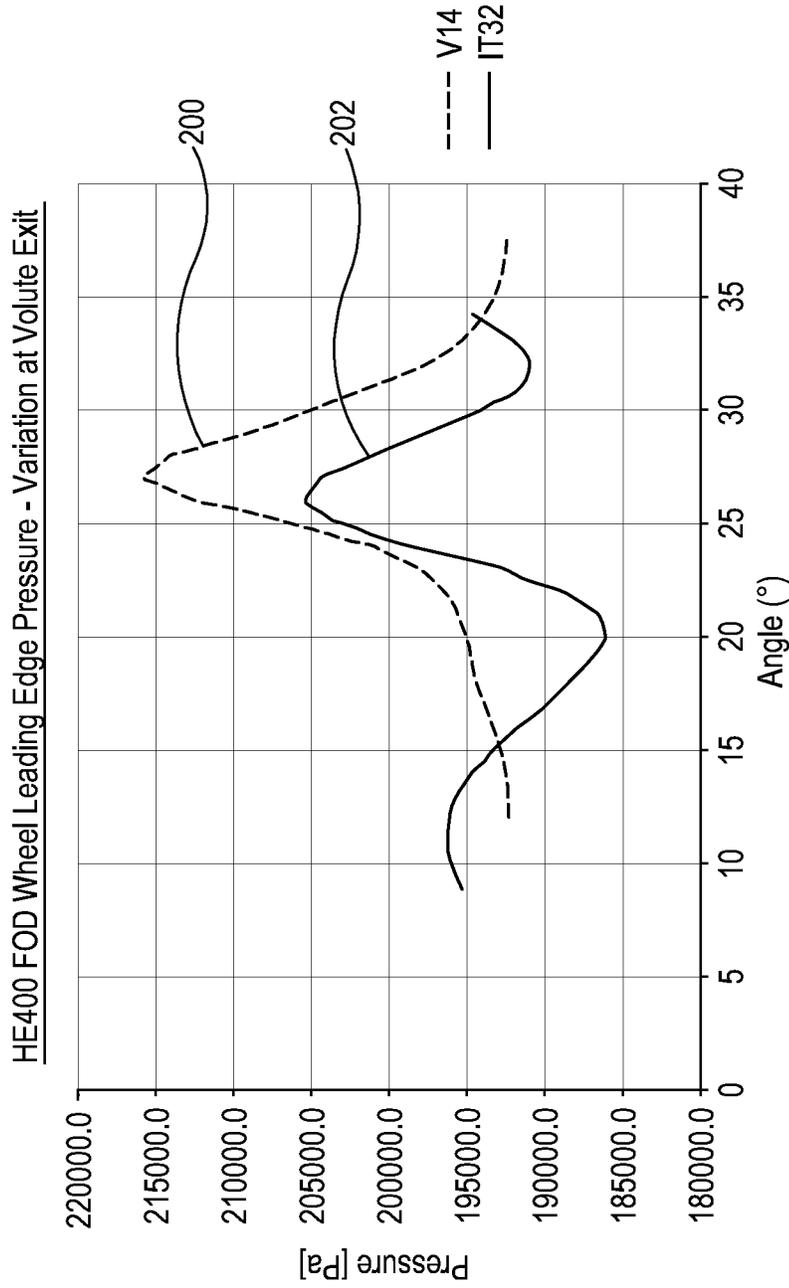


Fig. 14

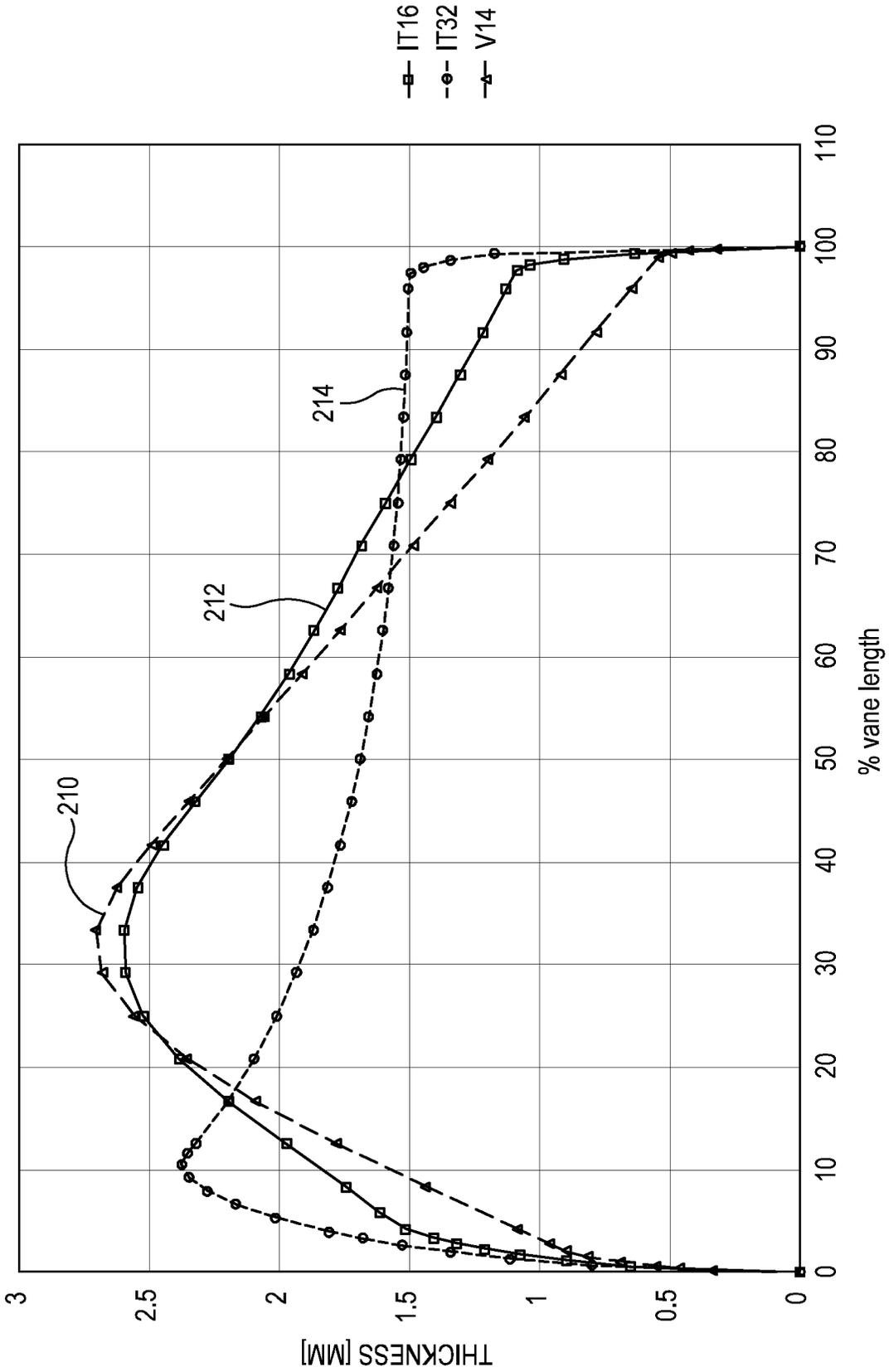


Fig. 15

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VARIABLE GEOMETRY TURBINE**CROSS-REFERENCE TO RELATED APPLICATIONS**

This application claims priority to International Patent Application No. PCT/GB2021/050506, filed Feb. 26, 2021, which claims priority to GB Patent Application No. 2002924.5, filed Feb. 28, 2020, the disclosures of which are hereby expressly incorporated by reference in their entirety.

FIELD

The present disclosure relates to a variable geometry turbine, particularly, but not exclusively, for use in a turbocharger of an internal combustion engine.

BACKGROUND

Turbochargers are known devices for supplying air to the intake of an internal combustion engine at pressures above atmospheric pressure (boost pressures). A conventional turbocharger includes an exhaust gas driven turbine wheel mounted on a rotatable shaft within a turbine housing. Rotation of the turbine wheel rotates a compressor wheel that is mounted on the other end of the shaft and within a compressor housing. The compressor wheel delivers compressed air to the engine intake manifold. The turbocharger shaft is conventionally supported by journal and thrust bearings, including appropriate lubricating systems, located within a central bearing housing connected between the turbine and compressor wheel housings.

In known turbochargers, the turbine includes a turbine chamber within which the turbine wheel is mounted, an inlet passageway defined between facing radial walls arranged around the turbine chamber, an inlet volute arranged around the inlet passageway, and an outlet passageway extending from the turbine chamber. The passageways and chambers communicate in such a way that pressurised exhaust gas admitted to the inlet volute flows through the inlet passageway to the outlet passageway via the turbine and rotates the turbine wheel. It is also known to trim turbine performance by providing vanes, referred to as nozzle vanes, in the inlet passageway so as to deflect gas flowing through the inlet passageway towards the direction of rotation of the turbine wheel.

Turbines may be of a fixed or variable geometry type. Variable geometry turbines differ from fixed geometry turbines in that the size of the inlet passageway can be varied to optimise gas flow velocities over a range of mass flow rates so that the power output of the turbine can be varied to suit varying engine demands. For instance, when the volume of exhaust gas being delivered to the turbine is relatively low, the velocity of the gas reaching the turbine wheel is maintained at a level that ensures efficient turbine operation by reducing the size of the inlet passageway.

In one known type of variable geometry turbine, an axially movable wall member, generally referred to as a “nozzle ring”, defines one wall of the inlet passageway. Hereinafter, the term “nozzle ring” may be used interchangeably with the phrase “movable wall member”. The position of the nozzle ring relative to a facing wall of the inlet passageway is adjustable to control the axial width of the inlet passageway. Thus, for example, as gas flowing through the turbine decreases, the inlet passageway width may also be decreased to maintain gas velocity and to optimise turbine output. Such nozzle rings include a gener-

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ally annular wall and inner and outer axially extending flanges. The flanges extend into a cavity defined in the turbine housing, which is a part of the housing that in practice is provided by the bearing housing, which accommodates axial movement of the nozzle ring.

The nozzle ring may be provided with vanes that extend into the inlet passageway and through slots provided on the facing wall of the inlet passageway to accommodate movement of the nozzle ring. Alternatively, vanes may extend from the fixed wall through slots provided in the nozzle ring. Generally the nozzle ring is supported on rods extending parallel to the axis of rotation of the turbine wheel and is moved by an actuator that axially displaces the rods. Various forms of actuators are known for use in variable geometry turbines, including pneumatic, hydraulic and electric actuators that are mounted externally of the turbocharger and connected to the variable geometry system via appropriate linkages.

It may be desirable to provide a variable geometry turbine at least partially addresses one or more problems associated with known variable geometry turbines, whether identified herein or otherwise.

SUMMARY

According to a first aspect of the present disclosure there is provided a variable geometry turbine comprising: a turbine housing defining an inlet and an outlet; a turbine wheel rotatably mounted in the turbine housing between the inlet and the outlet such that the turbine wheel can rotate about an axis; a movable wall member mounted in the housing so as to be movable relative to the housing between at least a first position and a second position, the movable wall member partially defining an inlet passageway between the inlet and the turbine wheel, the inlet passageway being radially outboard of the turbine wheel, a dimension of the inlet passageway being dependent on the position of the movable wall member relative to the housing; and a plurality of vanes extending across the inlet passageway, the vanes being circumferentially spaced; wherein in cross section each of the vanes has an elongate shape extending from a leading edge which is closer to the inlet to a trailing edge which is closer to the turbine wheel and wherein a perpendicular thickness of the vane 5% along the length of the vane from the leading edge is at least 50% of the maximum perpendicular thickness of the vane.

It will be appreciated that as used here the perpendicular thickness of the vane is intended to mean the thickness perpendicular to a camber line of the vane.

The variable geometry turbine according to this aspect of the disclosure has vanes which have more bulbous leading edges, and which may have larger radii of curvature, than the vanes typically used in such variable geometry turbines. This is advantageous over existing designs, as now discussed.

The use of such a bulbous or blunt leading edge is contrary to the existing teaching in the art, which would prompt the skilled person to select a smaller thickness at the leading edge or the vanes in order to achieve better separation of the flow over the vanes (in turn, increasing the efficiency of the turbine). However, the inventors have realized that for a variable geometry turbine, the angle of attack of the flow of fluid over the vanes is dependent on the position of the movable wall member. The inlet passageway between the inlet and the turbine wheel is partially defined by the movable wall member and may also be partially defined by a second wall member (which may, for example,

be fixed relative to the housing or integral therewith). The position of the movable wall member may be characterized by a distance between the movable wall member and the second wall member. This distance may be referred to as a variable geometry gap, or "VG gap".

By increasing the thickness at the leading edge such that a perpendicular thickness of the vane 5% along the length of the vane from the leading edge is at least 50% of the maximum perpendicular thickness of the vane, the variable geometry turbine according to this aspect of the disclosure will operate with a relatively high efficiency over a larger range of angles of attack (and therefore, equivalently, over a larger range of positions of the movable wall member or VG gaps). Whereas prior art turbines may be very efficient for a particular position of the movable wall member and very inefficient at other positions of the movable wall member, the variable geometry turbine according to this aspect of the disclosure can operate with a relatively high efficiency over a significantly larger range of positions of the movable wall member.

Typically, it may be intended for a variable geometry turbine to operate at a particular design configuration (or design point) and convention wisdom would suggest that the vanes be arranged to maximize the efficiency of the turbine under these conditions. For example, a variable geometry turbine may be optimized for a flush gap arrangement wherein the VG gap substantially matches a width of a leading edge (or tip) of the turbine wheel.

Although the variable geometry turbine may operate at the design configuration for the majority of the time, the variable geometry will also operate at other VG gaps. The inventors have realized that with prior art arrangements, whilst being the most efficient (time-averaged) arrangement, the efficiency at some other configurations that are far from the design configuration could be significantly smaller. Perhaps more importantly, the inventors have realized that with prior art arrangements some off design configurations large static pressure fluctuations can be induced at the leading edge of the turbine wheel, which can increase high cycle fatigue to the detriment of the lifetime of the variable geometry turbine. This is addressed by the variable geometry turbine according to this aspect of the disclosure.

The perpendicular thickness of the vane 5% along the length of the vane from the leading edge may be at least 55% of the maximum perpendicular thickness of the vane. The perpendicular thickness of the vane 5% along the length of the vane from the leading edge is at least 60% of the maximum perpendicular thickness of the vane. In some embodiments, the perpendicular thickness of the vane 5% along the length of the vane from the leading edge may be at least 70% of the maximum perpendicular thickness of the vane or even 80% of the maximum perpendicular thickness of the vane.

A perpendicular thickness of the vane 95% along the length of the vane from the leading edge may be at least 40% of the maximum perpendicular thickness of the vane.

Advantageously, such an arrangement increases the foreign object damage (FOD) tolerance of the vanes.

The perpendicular thickness of the vane 95% along the length of the vane from the leading edge may be at least 45% of the maximum perpendicular thickness of the vane. The perpendicular thickness of the vane 95% along the length of the vane from the leading edge may be at least 50% of the maximum perpendicular thickness of the vane. The perpendicular thickness of the vane 95% along the length of the vane from the leading edge may be at least 55% of the maximum perpendicular thickness of the vane. The perpen-

dicular thickness of the vane 95% along the length of the vane from the leading edge may be at least 60% of the maximum perpendicular thickness of the vane.

The vanes and the turbine wheel may be arranged such that a ratio of a radius of the trailing edge of each of the vanes to a radius of a leading edge of the turbine wheel is 1.2 or greater.

The ratio of the radius of the trailing edge of each of the vanes to the radius of the leading edge of the turbine wheel may be in the range 1.2 to 1.25.

Whilst increasing the foreign object damage (FOD) tolerance of the vanes, increasing the dimension at the trailing edge (for example such that a perpendicular thickness of the vane 95% along the length of the vane from the leading edge is at least 40% of the maximum perpendicular thickness of the vane) can increase the length of the wake formed downstream of each vane. Advantageously, increasing the ratio of the radius of the trailing edge of each of the vanes to the radius of the leading edge of the turbine wheel to 1.2 or greater may allow this wake to dissipate sufficiently so as to reduce the forcing function at a tip of the turbine wheel.

The vanes and the turbine wheel may be arranged such that a ratio of a radius of the leading edge of each of the vanes to a radius of the trailing edge of each of the vanes is 1.2 or greater.

The vanes and the turbine wheel may be arranged such that a ratio of a solidity ratio of the vanes in in the range 1.1 to 1.3.

The ratio of the length of the passageway defined between each pair of adjacent vanes to the width of said passageway may be referred to as the solidity ratio. A higher solidity ratio results in a larger vane overlap. In turn, this results in increases control over the flow between adjacent vanes.

The leading edge of the vanes may be provided with an elliptical end treatment having a ratio of the major axis to the minor axis of at least 1.5.

The elliptical end treatment may have a ratio of the major axis to the minor axis of 1.5. Alternatively, the elliptical end treatment may have a ratio of the major axis to the minor axis of 2.0.

The vanes may be arranged so as to produce a double wake variation in the static pressure around a circumference of the turbine wheel.

The static pressure trace around a circumference of the turbine at the trailing edge of each of the vanes may be referred to as the forcing function. Naively, one may expect the forcing function to have some areas of low pressure corresponding to the wake of each vane interspersed by areas of high pressure corresponding to the flow of fluid through the passageway defined between each pair of adjacent vanes. That is, one may expect the forcing function to be dominated by a Fourier component that corresponds to the number of the plurality of vanes (which may be referred to as a vane order oscillation).

Whilst increasing the foreign object damage (FOD) tolerance of the vanes, increasing the dimensions of the trailing edge of the vanes can increase the length of the wake formed downstream of each vane.

Shaping the vanes such that each vane produces a double wake in the forcing function reduces the overall amplitude of the forcing function. Advantageously, this can reduce the overall magnitude of the forcing function sufficiently such that even if the wake of the vanes has not fully dissipated the forcing function may be at an acceptably low level.

The vanes may have a shape at least partially defined by a thickness distribution that exponentially reduces from the

leading edge to the trailing edge and having an end treatment at each of the leading and trailing edges.

Such a thickness distribution may induce a double wake. The thickness distribution may be the thickness distribution in Table 7. The actual thickness of the vanes, with the end treatment at each of the leading and trailing edges, may be the thickness distribution in Table 14.

The vanes may have a shape at least partially defined by an angular distribution that is more tangential at the leading edge than the trailing edge.

Such an angular distribution may aid in the induction of a double wake. The angular distribution may be the angular distribution in Table 8.

According to a second aspect of the disclosure there is provided a variable geometry turbine comprising: a turbine housing defining an inlet and an outlet; a turbine wheel rotatably mounted in the turbine housing between the inlet and the outlet such that the turbine wheel can rotate about an axis; a movable wall member mounted in the housing so as to be movable relative to the housing between at least a first position and a second position, the movable wall member partially defining an inlet passageway between the inlet and the turbine wheel, the inlet passageway being radially outboard of the turbine wheel, a dimension of the inlet passageway being dependent on the position of the movable wall member relative to the housing; and a plurality of vanes extending across the inlet passageway, the vanes being circumferentially spaced; wherein in cross section each of the vanes has an elongate shape extending from a leading edge which is closer to the inlet to a trailing edge which is closer to the turbine wheel and wherein a perpendicular thickness of the vane 95% along the length of the vane from the leading edge is at least 40% of the maximum perpendicular thickness of the vane; and wherein the vanes and the turbine wheel are arranged such that a ratio of a radius of the trailing edge of each of the vanes to a radius of a leading edge of the turbine wheel is 1.2 or greater.

Advantageously, increasing a dimension of the trailing edge of each of the vanes such that a perpendicular thickness of the vane 95% along the length of the vane from the leading edge is at least 40% of the maximum perpendicular thickness of the vane increases the foreign object damage tolerance of the vanes. Whilst increasing the foreign object damage (FOD) tolerance of the vanes, increasing the dimension of the trailing edge can increase the length of the wake formed downstream of each vane. However, advantageously, increasing the ratio of the radius of the trailing edge of each of the vanes to the radius of the leading edge of the turbine wheel to 1.2 or greater may allow this wake to dissipate sufficiently so as to reduce the forcing function at a tip of the turbine wheel.

The perpendicular thickness of the vane 95% along the length of the vane from the leading edge may be at least 45% of the maximum perpendicular thickness of the vane. The perpendicular thickness of the vane 95% along the length of the vane from the leading edge may be at least 50% of the maximum perpendicular thickness of the vane. The perpendicular thickness of the vane 95% along the length of the vane from the leading edge may be at least 55% of the maximum perpendicular thickness of the vane. The perpendicular thickness of the vane 95% along the length of the vane from the leading edge may be at least 60% of the maximum perpendicular thickness of the vane.

A perpendicular thickness of the vane 5% along the length of the vane from the leading edge may be at least 50% of the maximum perpendicular thickness of the vane.

The use of such a bulbous or blunt leading edge provides increased tolerance to different angles of attack and can reduce the forcing function.

The ratio of the radius of the trailing edge of each of the vanes to the radius of the leading edge of the turbine wheel may be in the range 1.2 to 1.25.

The vanes and the turbine wheel may be arranged such that a ratio of a radius of the leading edge of each of the vanes to a radius of the trailing edge of each of the vanes is 1.2 or greater.

The vanes and the turbine wheel may be arranged such that a ratio of a solidity ratio of the vanes in in the range 1.1 to 1.3.

The ratio of the length of the passageway defined between each pair of adjacent vanes to the width of said passageway may be referred to as the solidity ratio. A higher solidity ratio results in a larger vane overlap. In turn, this results in increases control over the flow between adjacent vanes.

The leading edge of the vanes may be provided with an elliptical end treatment having a ratio of the major axis to the minor axis of at least 1.5.

The elliptical end treatment may have a ratio of the major axis to the minor axis of 1.5. Alternatively, the elliptical end treatment may have a ratio of the major axis to the minor axis of 2.0.

According to a third aspect of the disclosure there is provided a variable geometry turbine comprising: a turbine housing defining an inlet and an outlet; a turbine wheel rotatably mounted in the turbine housing between the inlet and the outlet such that the turbine wheel can rotate about an axis; a movable wall member mounted in the housing so as to be movable relative to the housing between at least a first position and a second position, the movable wall member partially defining an inlet passageway between the inlet and the turbine wheel, the inlet passageway being radially outboard of the turbine wheel, a dimension of the inlet passageway being dependent on the position of the movable wall member relative to the housing; and a plurality of vanes extending across the inlet passageway, the vanes being circumferentially spaced; wherein in cross section each of the vanes has an elongate shape extending from a leading edge which is closer to the inlet to a trailing edge which is closer to the turbine wheel and wherein the vanes are arranged so as to produce a double wake variation in the static pressure around a circumference of the turbine wheel.

The static pressure trace around a circumference of the turbine at the trailing edge of each of the vanes may be referred to as the forcing function. Naively, one may expect the forcing function to have some areas of low pressure corresponding to the wake of each vane interspersed by areas of high pressure corresponding to the flow of fluid through the passageway defined between each pair of adjacent vanes. That is, one may expect the forcing function to be dominated by a Fourier component that corresponds to the number of the plurality of vanes (which may be referred to as a vane order oscillation).

Whilst increasing the foreign object damage (FOD) tolerance of the vanes, increasing the dimensions of the trailing edge of the vanes can increase the length of the wake formed downstream of each vane.

Shaping the vanes such that each vane produces a double wake in the forcing function reduces the overall amplitude of the forcing function. Advantageously, this can reduce the overall magnitude of the forcing function sufficiently such that even if the wake of the vanes has not fully dissipated the forcing function may be at an acceptably low level.

The vanes may have a shape at least partially defined by a thickness distribution that exponentially reduces from the leading edge to the trailing edge and having an end treatment at each of the leading and trailing edges.

Such a thickness distribution may induce a double wake. The thickness distribution may be the thickness distribution in Table 7. The actual thickness of the vanes, with the end treatment at each of the leading and trailing edges, may be the thickness distribution in Table 14.

The vanes may have a shape at least partially defined by an angular distribution that is more tangential at the leading edge than the trailing edge.

Such an angular distribution may aid in the induction of a double wake. The angular distribution may be the angular distribution in Table 8.

According to a fourth aspect of the disclosure there is provided a variable geometry turbine comprising: a turbine housing defining an inlet and an outlet; a turbine wheel rotatably mounted in the turbine housing between the inlet and the outlet such that the turbine wheel can rotate about an axis; a movable wall member mounted in the housing so as to be movable relative to the housing between at least a first position and a second position, the movable wall member partially defining an inlet passageway between the inlet and the turbine wheel, the inlet passageway being radially outboard of the turbine wheel, a dimension of the inlet passageway being dependent on the position of the movable wall member relative to the housing; and a plurality of vanes extending across the inlet passageway, the vanes being circumferentially spaced; wherein in cross section each of the vanes has an elongate shape extending from a leading edge which is closer to the inlet to a trailing edge which is closer to the turbine wheel and wherein the vanes have a shape at least partially defined by a thickness distribution that exponentially reduces from the leading edge to the trailing edge and having an end treatment at each of the leading and trailing edges.

The thickness distribution may be the thickness distribution in Table 7. The actual thickness of the vanes, with the end treatment at each of the leading and trailing edges, may be the thickness distribution in Table 14.

The vanes may have a shape at least partially defined by an angular distribution that is more tangential at the leading edge than the trailing edge.

The angular distribution may be the angular distribution in Table 8.

According to a fifth aspect of the disclosure there is provided a variable geometry turbine comprising: a turbine housing defining an inlet and an outlet; a turbine wheel rotatably mounted in the turbine housing between the inlet and the outlet such that the turbine wheel can rotate about an axis; a movable wall member mounted in the housing so as to be movable relative to the housing between at least a first position and a second position, the movable wall member partially defining an inlet passageway between the inlet and the turbine wheel, the inlet passageway being radially outboard of the turbine wheel, a dimension of the inlet passageway being dependent on the position of the movable wall member relative to the housing; and a plurality of vanes extending across the inlet passageway, the vanes being circumferentially spaced; wherein in cross section each of the vanes has an elongate shape extending from a leading edge which is closer to the inlet to a trailing edge which is closer to the turbine wheel and wherein the vanes have a shape defined by the curves in Tables 9, 10, 11 and 12 multiplied by a scale factor.

The scale factor may be 1. Alternatively the scale factor may be less than or greater than 1.

It will be appreciated that the four curves given in Tables 9 to 12 define a shape and position of a single vane in a plane perpendicular to the axis. It will be appreciated that for the plurality of vanes to have a shape defined by the curves in Tables 9, 10, 11 and 12, all of the vanes have the shape as defined by the four curves given in Tables 9 to 12 but, in general, are disposed at different positions with respect to the axis. The vanes may be arranged evenly around the axis. The variable geometry turbine may comprise 14 vanes. Therefore, the positions of all the vanes may be given by rotating the x-y co-ordinates of the four curves given in Tables 9 to 12 about the origin by $n \cdot 360/14$ degrees, where n is an integer between 1 and 14 inclusive.

According to a sixth aspect of the disclosure there is provided a variable geometry turbine comprising: a turbine housing defining an inlet and an outlet; a turbine wheel rotatably mounted in the turbine housing between the inlet and the outlet such that the turbine wheel can rotate about an axis; a movable wall member mounted in the housing so as to be movable relative to the housing between at least a first position and a second position, the movable wall member partially defining an inlet passageway between the inlet and the turbine wheel, the inlet passageway being radially outboard of the turbine wheel, a dimension of the inlet passageway being dependent on the position of the movable wall member relative to the housing; and a plurality of vanes extending across the inlet passageway, the vanes being circumferentially spaced; wherein in cross section each of the vanes has an elongate shape extending from a leading edge which is closer to the inlet to a trailing edge which is closer to the turbine wheel and wherein the vanes have a shape at least partially defined by the thickness distribution in Table 1 and the angular distribution in Table 2.

The actual thickness of the vanes, with an end treatment at each of the leading and trailing edges, may be the thickness distribution in Table 13.

According to a seventh aspect of the disclosure there is provided variable geometry turbine comprising: a turbine housing defining an inlet and an outlet; a turbine wheel rotatably mounted in the turbine housing between the inlet and the outlet such that the turbine wheel can rotate about an axis; a movable wall member mounted in the housing so as to be movable relative to the housing between at least a first position and a second position, the movable wall member partially defining an inlet passageway between the inlet and the turbine wheel, the inlet passageway being radially outboard of the turbine wheel, a dimension of the inlet passageway being dependent on the position of the movable wall member relative to the housing; and a plurality of vanes extending across the inlet passageway, the vanes being circumferentially spaced; wherein in cross section each of the vanes has an elongate shape extending from a leading edge which is closer to the inlet to a trailing edge which is closer to the turbine wheel and wherein the vanes have a shape defined by the curves in Tables 3, 4, 5 and 6 multiplied by a scale factor.

The scale factor may be 1. Alternatively the scale factor may be less than or greater than 1.

It will be appreciated that the four curves given in Tables 3 to 6 define a shape and position of a single vane in a plane perpendicular to the axis. It will be appreciated that for the plurality of vanes to have a shape defined by the curves in Tables 3, 4, 5 and 6, all of the vanes have the shape as defined by the four curves given in Tables 3 to 6 but, in general, are disposed at different positions with respect to

the axis. The vanes may be arranged evenly around the axis. The variable geometry turbine may comprise 14 vanes. Therefore, the positions of all the vanes may be given by rotating the x-y co-ordinates of the four curves given in Tables 3 to 6 about the origin by $n \cdot 360/14$ degrees, where n is an integer between 1 and 14 inclusive.

According to an eighth aspect of the disclosure there is provided a movable wall member for use in the variable geometry turbine of any of the first, second, third, fourth, fifth, sixth or seventh aspects of the disclosure.

According to a ninth aspect of the disclosure there is provided a method for designing the vanes for a variable geometry turbine, the method comprising: selecting a thickness distribution; and applying an edge treatment to each of the leading edge and trailing edge, the edge treatment for the leading edge being elliptical in cross-section, having a ratio between the minor and major lengths of 1.5 or more; such that a perpendicular thickness of the resultant vane 5% along the length of the vane from the leading edge is at least 50% of the maximum perpendicular thickness of the vane.

Optionally, the method may further comprise: selecting a radius of the trailing edge of the vanes such that a ratio of the radius of the trailing edge of the vanes to a radius of a leading edge of the turbine wheel is within the range 1.2 to 1.25.

Optionally, the method may further comprise: selecting an outer diameter of the vane leading edge such that the ratio of the radius of the leading edge of the vanes to the radius of the trailing edge of the vanes is 1.2.

Optionally, the selection of the thickness distribution and the application of the edge treatment to each of the leading edge and trailing edge may be such that a perpendicular thickness of the resultant vane 95% along the length of the vane from the leading edge is at least 40% of the maximum perpendicular thickness of the vane.

According to a tenth aspect of the disclosure there is provided a method for designing the vanes for a variable geometry turbine having a turbine wheel, the method comprising: selecting a radius of the trailing edge of the vanes such that a ratio of the radius of the trailing edge of the vanes to a radius of a leading edge of the turbine wheel is within the range 1.2 to 1.25; and selecting an outer diameter of the vane leading edge such that the ratio of the radius of the leading edge of the vanes to the radius of the trailing edge of the vanes is 1.2.

According to an eleventh aspect of the disclosure there is provided a method for designing the vanes for a variable geometry turbine having a turbine wheel, the method comprising: selecting a thickness distribution of the vanes to provide a rapid reduction in vane thickness between the leading and trailing edges.

The method may further comprise: selecting an angular distribution of the vanes wherein the angular distribution is more tangential at the leading edge than at the trailing edge.

It will be appreciated that where appropriate any of the above aspects may incorporate one or more features of any of the other aspects.

BRIEF DESCRIPTION OF THE DRAWINGS

Specific embodiments of the present disclosure will now be described, by way of example, with reference to the accompanying drawings, of which:

FIG. 1 shows a turbocharger which may incorporate a variable geometry turbine in accordance with an embodiment of the present disclosure;

FIG. 2 illustrates the steps of a conventional method or process for designing the vanes for a variable geometry turbine of the type of turbine shown in FIG. 1;

FIG. 3 illustrates the steps of a first new method or process according to an embodiment of the disclosure for designing the vanes for a variable geometry turbine of the type of turbine shown in FIG. 1;

FIG. 4 illustrates the steps of a second new method or process according to an embodiment of the disclosure for designing the vanes for a variable geometry turbine of the type of turbine shown in FIG. 1;

FIG. 5A shows an arrangement of vanes designed according to the known method shown in FIG. 2 in a plane perpendicular to the turbocharger axis;

FIG. 5B shows the thickness distribution of the vanes shown in FIG. 5A as a percentage along the length of the vanes;

FIG. 5C shows the angular distribution of the vanes shown in FIG. 5A as a percentage along the length of the vanes;

FIG. 6A shows an arrangement of vanes designed according to the new method shown in FIG. 3 in a plane perpendicular to the turbocharger axis;

FIG. 6B shows the thickness distribution of the vanes shown in FIG. 6A as a percentage along the length of the vanes;

FIG. 6C shows the angular distribution of the vanes shown in FIG. 6A as a percentage along the length of the vanes;

FIG. 7A shows an arrangement of vanes designed according to the new method shown in FIG. 4 in a plane perpendicular to the turbocharger axis;

FIG. 7B shows the thickness distribution of the vanes shown in FIG. 7A as a percentage along the length of the vanes;

FIG. 7C shows the angular distribution of the vanes shown in FIG. 7A as a percentage along the length of the vanes;

FIGS. 8A to 8C illustrate the performance of the arrangement of vanes shown in FIG. 5A for an exhaust flow for which the arrangement has been designed;

FIGS. 9A to 9C illustrate the performance of the arrangement of vanes shown in FIG. 5A for an exhaust flow for which the arrangement has not been designed;

FIGS. 10A to 10C illustrate the performance of the arrangement of vanes shown in FIG. 6A for an exhaust flow for which the arrangement has been designed;

FIGS. 11A to 11C illustrate the performance of the arrangement of vanes shown in FIG. 6A for an exhaust flow for which the arrangement has not been designed;

FIGS. 12A to 12C illustrate the performance of the arrangement of vanes shown in FIG. 7A for an exhaust flow for which the arrangement has been designed;

FIGS. 13A to 13C illustrate the performance of the arrangement of vanes shown in FIG. 7A for an exhaust flow for which the arrangement has not been designed;

FIG. 14 shows the static pressure variation over an angular region of the turbine wheel corresponding to a single vane for the arrangements shown in FIGS. 5A and 7A; and

FIG. 15 shows the actual thicknesses of the vanes shown in FIGS. 5A, 6A and 7A respectively, as a percentage of the vane length.

DETAILED DESCRIPTION

FIG. 1 shows a turbocharger 1 which may incorporate a variable geometry turbine in accordance with an embodi-

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ment of the present disclosure. The turbocharger **1** comprises a turbine housing **2** and a compressor housing **3** interconnected by a central bearing housing **4**. A turbocharger shaft **5** extends from the turbine housing **2** to the compressor housing **3** through the bearing housing **4**. A turbine wheel **6** is mounted on one end of the shaft **5** for rotation within the turbine housing **2**, and a compressor wheel **7** is mounted on the other end of the shaft **5** for rotation within the compressor housing **3**. The shaft **5** rotates about turbocharger axis **8** on bearing assemblies located in the bearing housing **4**.

It will be appreciated that the turbine housing **2** and an axial end of the bearing housing **4** together form a housing of the variable geometry turbine, in which the turbine wheel **6** is supported for rotation about turbocharger axis **8**.

The turbine housing **2** defines an inlet volute **9** to which exhaust gas from an internal combustion engine (not shown) is delivered. The exhaust gas flows from the inlet volute **9** to an axial outlet passage **10** via an inlet passageway **11** and the turbine wheel **6**. The inlet passageway **11** is defined between two axially spaced walls. In particular, the inlet passageway **11** is defined on one side by a face of a movable wall member **12**, commonly referred to as a “nozzle ring,” and on the opposite side by a shroud **13**. The shroud **13** covers the opening of a generally annular recess **14** in the turbine housing **2**.

As will be appreciated by the skilled person, the inlet volute **9** may comprise a generally toroidal volume (defined by the turbine housing **2**) and an inlet arranged to direct exhaust gas from an internal combustion engine tangentially into the generally toroidal volume. As exhaust gas enters the inlet volute **9** it flows circumferentially around the generally toroidal volume and radially inwards towards the inlet passageway **11**. In the vicinity of the inlet, there is provided a wall or “tongue” **18** which serves to separate the generally toroidal volume in the vicinity of the inlet of the volute **9** from the inlet passageway **11** of the turbine. The tongue **18** may help to guide the exhaust gas circumferentially around the generally toroidal volume and may also aid the mixing of the generally linear gas flowing into the volute **9** with the circumferential gas flow around the generally toroidal volume. In the cross section shown in FIG. 1, the tongue **18** is visible on one side of the axis **8** only.

The movable wall member **12** supports an array of circumferentially and equally spaced inlet vanes **15** each of which extends across the inlet passageway **11**. The vanes **15** are orientated to deflect gas flowing through the inlet passageway **11** towards the direction of rotation of the turbine wheel **6**. The shroud **13** is provided with suitably configured slots for receipt of the vanes **15** such that as the movable wall member **12** moves axially towards the shroud **13**, a distal end of each of the vanes **15** moves through one of said slots and protrudes into the recess **14**.

Accordingly, by appropriate control of the actuator (which may for instance be pneumatic or electric), the axial position of the movable wall member **12** can be controlled. The speed of the turbine wheel **6** is dependent upon the velocity of the gas passing through the inlet passageway **11**. For a fixed rate of mass of gas flowing into the inlet passageway **11**, the gas velocity is a function of the width of the inlet passageway **11**, the width being adjustable by controlling the axial position of the movable wall member **12**. As the width of the inlet passageway **11** is reduced, the velocity of the gas passing through it increases. FIG. 1 shows the nozzle ring **12** disposed between a fully open position and a fully closed position such that the width of

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inlet passageway **11** is greater than a minimum width and smaller than a maximum width.

The (axial) width of the inlet passageway **11** between the movable wall member **12** and the shroud **13** may be referred to as a variable geometry gap or a VG gap.

It will be appreciated that the exhaust gases spiral generally radially inwards through the inlet passageway **11** towards the turbine wheel **6**. Accordingly, it will be appreciated that, unless stated otherwise, as used herein the leading edge of a vane **15** shall be understood to be a radially outer end of the vane **15** and the trailing edge of a vane **15** shall be understood to be a radially inner end of the vane **15**.

Gas flowing from the inlet volute **9** to the outlet passage **10** passes over the turbine wheel **6** and as a result torque is applied to the shaft **5** to drive the compressor wheel **7**. Rotation of the compressor wheel **7** within the compressor housing **3** pressurises ambient air present in an air inlet **16** and delivers the pressurised air to an air outlet volute **17** from which it is fed to an internal combustion engine (not shown).

The movable wall member (or nozzle ring) **12** comprises a generally annular wall **20** and radially inner and outer flanges **21**, **22** extending axially from the generally annular wall **20**.

A cavity **25** is provided in the housing of the variable geometry turbine for receipt of the radially inner and outer flanges **21**, **22** of the movable wall member **12**. It will be appreciated that the cavity **25** is formed on an axial end of the bearing housing **4**, which cooperates with the turbine housing **2** to form the housing of the variable geometry turbine.

As the movable wall member **12** moves axially, the extent to which the radially inner and outer flanges **21**, **22** of the movable wall member **12** are received in the cavity **25** varies. The movable wall member **12** is movable between a fully opened position and a fully closed position. When disposed in the fully opened position, the radially inner and outer flanges **21**, **22** of the movable wall member **12** may contact a base surface **26** of the cavity **25**. That is, a portion of the base surface **26** of the cavity **25** may serve as a physical stop to limit the range of axial movement of the movable wall member **12**.

Inner and outer sealing rings **27**, **28** are provided to seal the movable wall member **12** with respect to surfaces of the cavity **25**, whilst allowing the movable wall member **12** to slide within the cavity **25**. The inner sealing ring **27** is supported within an annular groove formed in a radially inner curved surface of the cavity **25** and bears against the inner flange **21** of the movable wall member **12**. The outer sealing ring **28** is supported within an annular groove formed in a radially outer curved surface of the cavity **25** and bears against the outer flange **22** of the movable wall member **12**.

In some embodiments a plurality of axially extending apertures may be provided through the generally annular wall **20** of the movable wall member **12**. The apertures may be referred to as balancing apertures. The balancing apertures may connect the inlet **11** to the cavity **25**, such that the inlet **11** and the cavity **25** are in fluid communication via the apertures. In use, the balancing apertures serve to reduce pressure differences across the generally annular wall **20** of the movable wall member **12** and thereby reduce loads applied to the face of the generally annular wall **20** of the movable wall member **12**.

In use, as air flows radially inwards through the turbine inlet **11**, it flows between adjacent vanes **15**, which can be regarded as defining a vane passage. The turbine inlet **11** has

a reduced radial flow area in the region of the vane passage with the effect that the inlet gas speed increases through the vane passage with a corresponding drop in pressure in this region of the movable wall member **12**.

Embodiments of the present disclosure relate to variable geometry turbines of the type of turbine shown in FIG. **1** which have new arrangements of inlet vanes **15** which extend across the inlet passageway **11**. In particular, embodiments of the present disclosure relate to vanes **15** having new shapes and configurations with respect to known vanes **15**. Some embodiments of the present disclosure may relate to a movable wall member **12** (or nozzle ring) or even merely to a vane **15**.

As explained further below, some embodiments of the present disclosure relate to vanes **15** having shapes and configurations which would be contrary to prejudices of the skilled person. Some embodiments of the present disclosure relate to new methods for designing arrangements **110** of inlet vanes **15** which extend across the inlet passageway **11** of a variable geometry turbine of the type of turbine shown in FIG. **1**.

Some embodiments of the present disclosure relate to new inlet vanes **15** which have a shape and configuration which results in a reduction in the amplitude of azimuthal (static) pressure variations around the circumference of the turbine wheel **6**. Such azimuthal pressure variations around the circumference of the turbine wheel **6** may be referred to herein as a forcing function. In particular, some embodiments of the present disclosure relate to new inlet vanes **15** which have a shape and configuration which results in a reduction in the amplitude of azimuthal pressure variations around the circumference of the turbine wheel **6** over a range of different VG gaps. This is beneficial since large pressure fluctuations around the circumference of the turbine wheel **6** (which the blades of the turbine wheel **6** move through) will cause oscillating deformation or vibration of the blades of the turbine wheel **6**. In turn, this can lead to high cycle fatigue.

Some embodiments of the present disclosure relate to new inlet vanes **15** which have a larger, more bulbous (or, alternatively, less pointy) leading edge **112a** profile with respect to known vanes **15**. This is advantageous over existing designs, as now discussed.

The use of such a bulbous or blunt leading edge **112a** is contrary to the existing teaching in the art, which would prompt the skilled person to select a smaller radius of curvature at the leading edge or the vanes in order to achieve better separation of the flow over the vanes (in turn, increasing the efficiency of the turbine). However, the inventors of the present disclosure have realized that for a variable geometry turbine, the angle of attack of the flow of fluid over the vanes **112** is dependent on the position of the movable wall member **12** (i.e. the VG gap). By increasing the radius of curvature of the vanes **112** at the leading edge **112a** the variable geometry turbines according to some embodiments of the disclosure will operate with a relatively high efficiency over a larger range of angles of attack (and therefore, equivalently, over a larger range of positions of the movable wall member **12** or VG gaps). In addition, the variable geometry turbines according to some embodiments of the disclosure will maintain the amplitude of the forcing function relatively low over a significantly larger range of positions of the movable wall member.

At least some increased tolerance to variation in angle of attack is expected for a vanes having a perpendicular thick-

ness 5% along the length of the vane from the leading edge of at least 50% of the maximum perpendicular thickness of the vane.

Some embodiments of the present disclosure relate to new inlet vanes **15** which have a larger, more bulbous (or, alternatively, less pointy) trailing edge profile with respect to known vanes **15**. Advantageously, such an arrangement increases the foreign object damage (FOD) tolerance of the vanes **15**.

Some new methods for designing arrangements of inlet vanes **15** which extend across the inlet passageway **11** of a variable geometry turbine of the type of turbine shown in FIG. **1** are now discussed with reference to FIGS. **2** to **4**.

In order to better understand the new methods for designing the vanes **15** for a variable geometry turbine of the type of turbine shown in FIG. **1**, it is useful to consider the steps of a conventional method or process for designing these vanes **15**.

FIG. **2** illustrates the steps of a conventional method or process for designing the vanes **15** for a variable geometry turbine of the type of turbine shown in FIG. **1**.

At step **50**, the radius of the trailing edge of the vanes **15** is selected so as to place the vanes **15** as close to the tip (or leading edge) of the turbine wheel **6** as the architecture allows. For example a small clearance is provided between the trailing edge of the vanes **15** and the wheel but this clearance is minimised.

At step **52**, the outer diameter of the vane leading edge is selected so as to provide some overlap of the vanes. That is, the azimuthal extent of the vanes **15** is such that the leading edge of one vane will overlap slightly in an azimuthal direction with the trailing edge of an adjacent vane.

At step **54**, an angle of the leading edge of the vane is selected so as to align with the expected angle of flow into the nozzle ring **12**.

At step **56**, an angle of the trailing edge of the vane is selected so as to provide the correct wheel inlet flow for the turbine wheel **6**.

At step **58**, a vane angle distribution is selected to provide a target throat area and to perform the majority of turning of the fluid in first 25% of the vane length. The target throat area is selected in order to achieve a target mass flow range. In turn, this target mass flow is selected to maximise the efficiency of the turbine.

At step **60**, a vane thickness distribution is selected using a NACA aerofoil having a specified the thickness to length ratio.

Finally, at step **62** an edge treatment is applied to each of the leading edge and trailing edge. These edge treatments are circular in cross-section, i.e. ellipses having a ratio between the minor and major lengths of 1.0.

It will be appreciated that these steps **50-62** are interrelated and may be carried out in parallel rather than sequentially. Alternatively, these steps **50-62** may be carried out in a different order. Together steps **50-62** define the constraints that are applied to the design of known vanes.

FIG. **3** illustrates the steps of a first new method or process according to an embodiment of the disclosure for designing the vanes **15** for a variable geometry turbine of the type of turbine shown in FIG. **1**.

At step **70**, the radius of the trailing edge of the vanes **15** is selected such that the ratio of the radius of the trailing edge of the vanes **15** to the radius of the tip (or leading edge) of the turbine wheel **6** is within the range 1.2 to 1.25. This is a significant departure from existing methods (see step **50** in FIG. **2**). This change, which would be contrary to the prejudice of the skilled person, has a number of advantages.

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First, by moving the vanes **15** further away from the turbine wheel **6**, the wake formed downstream of each vane will dissipate more before it reaches the turbine wheel **6**, decreasing the forcing function. Furthermore, this may allow for a larger than standard dimension of the trailing edge of the vanes **15** (see step **78**) and still allow sufficient distance for the wake to dissipate sufficiently to provide a forcing function having a reasonable amplitude.

At step **72**, the outer diameter of the vane leading edge is selected such that the ratio of the radius of the leading edge of the vanes **15** to the radius of the trailing edge of the vanes **15** is 1.2 so as to provide a solidity ratio of 1.1 to 1.3. The vane solidity ratio is the ratio of the vane length to the width of the passage defined between each pair of adjacent vanes. A higher ratio will result in a longer vane to passage width which will result in a vane overlap. Increasing the vane overlap provides better control of the flow between the vanes.

At step **74**, an angle of the trailing edge of the vane is selected so as to provide the correct wheel inlet flow for the turbine wheel **6**.

At step **76**, an angle distribution of the vane **15** is selected so as to align with the expected angle of flow into the nozzle ring **12** and to provide a target throat area. The target throat area is selected in order to achieve a target mass flow range. In turn, this target mass flow is selected to maximise the efficiency of the turbine.

At step **78**, the thickness of the vane **15** at the trailing edge is increased (relative to known vane shapes) to provide increased tolerance to foreign object damage (FOD).

At step **80** the thickness of the vane **15** at the leading edge is increased (relative to known vane shapes). As discussed above, this is a significant departure from existing methods and would be contrary to the prejudice of the skilled person. By increasing the thickness of the vanes at the leading edge the variable geometry turbine will operate with a relatively high efficiency over a larger range of angles of attack (and therefore, equivalently, over a larger range of positions of the movable wall member **12** or VG gaps). In addition, the variable geometry turbine will maintain the amplitude of the forcing function relatively low over a significantly larger range of positions of the movable wall member **12**.

At step **82** the thickness distribution of the vane **15** is selected to minimise pressure loss.

Finally, at step **84** an edge treatment is applied to each of the leading edge and trailing edge. The edge treatment for the leading edge is elliptical in cross-section, having a ratio between the minor and major lengths of 1.5. The edge treatment for the trailing edge is circular in cross-section, i.e. an ellipse having a ratio between the minor and major lengths of 1.0.

It will be appreciated that vanes **15** designed using the method illustrated in FIG. **3** have at least the following distinguishing features over existing arrangements: the vanes **15** are radially further out from the turbine wheel **6**, the vanes have an increased trailing edge, the vanes have an increased leading edge and the edge treatment for the leading edge of the vanes is elliptical in cross-section.

FIG. **4** illustrates the steps of a second new method or process according to an embodiment of the disclosure for designing the vanes **15** for a variable geometry turbine of the type of turbine shown in FIG. **1**. In particular, the method illustrated in FIG. **4** is particularly suitable for a turbine wherein there is reduced freedom to move the vanes **15** radially outwards sufficiently far so as to use the method illustrated in FIG. **3**.

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At step **90**, the radius of the trailing edge of the vanes **15** is selected. In particular, the radius of the trailing edge of the vanes **15** is selected so as to be increased relative to the arrangement resulting from the known method of FIG. **2** but which is reduced relative to the new method of FIG. **3**, for example, due to packing requirements. That is, it may be that due to packing or space requirements it is not possible to achieve a ratio of the radius of the trailing edge of the vanes **15** to the radius of the tip (or leading edge) of the turbine wheel **6** is within the range 1.2 to 1.25. With this arrangement a smaller ratio of the radius of the trailing edge of the vanes **15** to the radius of the tip of the turbine wheel **6**, for example around 1.1 may be selected at step **90**.

At step **92**, the outer diameter of the vane leading edge is selected. Again, the outer diameter of the vane leading edge is reduced relative to the new method of FIG. **3**, for example, due to packing requirements. In turn, this may result in a reduced solidity ratio.

At step **94**, an angle of the trailing edge of the vane is selected so as to provide the correct wheel inlet flow for the turbine wheel **6**.

At step **96**, in contrast to existing methods, the angle distribution of the vane **15** is selected so as to be more tangential than existing methods. The angle distribution of the vane **15** is selected to match the expected angle of flow into the nozzle ring **12** and to provide a target throat area. The target throat area is selected in order to achieve a target mass flow range. In turn, this target mass flow is selected to maximise the efficiency of the turbine.

At step **98**, the thickness of the vane **15** at the trailing edge is increased (relative to known vane shapes) to provide increased tolerance to foreign object damage (FOD).

At step **100** the thickness of the vane **15** at the leading edge is increased (relative to known vane shapes). As discussed above, this is a significant departure from existing methods and would be contrary to the prejudice of the skilled person. By increasing the thickness of the vanes at the leading edge the variable geometry turbine will operate with a relatively high efficiency over a larger range of angles of attack (and therefore, equivalently, over a larger range of positions of the movable wall member **12** or VG gaps). In addition, the variable geometry turbine will maintain the amplitude of the forcing function relatively low over a significantly larger range of positions of the movable wall member **12**.

At step **102** the thickness distribution of the vane **15** is selected to provide a rapid (for example exponential) reduction in vane thickness between the leading and trailing edges. Again, this is a significant departure from existing arrangements which would typically increase from the leading edge up to a thicker central portion of the vane before decreasing towards the trailing edge.

Finally, at step **104** an edge treatment is applied to each of the leading edge and trailing edge. The edge treatment for the leading edge is elliptical in cross-section, having a ratio between the minor and major lengths of 2.0. The edge treatment for the trailing edge is circular in cross-section, i.e. an ellipse having a ratio between the minor and major lengths of 1.0.

Some new inlet vanes **15** which extend across the inlet passageway **11** of a variable geometry turbine of the type of turbine shown in FIG. **1** are now discussed with reference to FIGS. **5A** to **7C**.

In general, the shape of a vane is defined by two opposed surfaces (which may be referred to as the pressure and suction surfaces of the vane) extending between the leading edge and the trailing edge. As previously states, the leading

edge of a vane shall be understood to be a radially outer end of the vane and the trailing edge of a vane shall be understood to be a radially inner end of the vane.

In the following, a straight line connecting the leading edge to the trailing edge is referred to as a chord. Similarly, a line connecting the leading edge to the trailing edge which bisects the vane (i.e. is halfway between the two opposed surfaces of the vane) is referred to as a camber or camber line. It will be appreciated that, in general, the camber of a vane is curved.

As used herein, an angular distribution of a vane is intended to mean the angle between a tangent to the camber line and a radial direction (relative to the turbocharger axis **8**) as a function of position along the vane. The angular distribution defines the camber of the vane.

As used herein, a thickness distribution of a vane is intended to mean the thickness of the aerofoil perpendicular to a camber line of the vane as a function of position along the vane.

Together, the angular distribution and the thickness distribution define an envelope which defines the general shape of the vane. This envelope (which has blunt, flat edges at the leading edge and trailing edge) is then modified by the edge treatments described above (see steps **62**, **84**, **104** in FIGS. **2**, **3**, **4**), which smooths or removes these sharp edges at the leading and trailing edge.

FIG. **5A** shows an arrangement **110** of vanes **112** designed according to the known method shown in FIG. **2** in a plane perpendicular to the turbocharger axis **8**. The arrangement **110** comprises 14 vanes **112** arranged evenly around the turbocharger axis **8**.

FIG. **5B** shows the thickness distribution **114** of the vanes **112** shown in FIG. **5A** as a percentage along the length of the vanes **112** (from the leading edge **112a** to the trailing edge **112b**).

FIG. **5C** shows the angular distribution **116** of the vanes **112** shown in FIG. **5A** as a percentage along the length of the vanes **112** (from the leading edge **112a** to the trailing edge **112b**).

In the arrangement **110** of vanes **112**, the ratio of the radius of the trailing edge **112b** of the vanes **112** to the radius of the tip (or leading edge) of the turbine wheel **6** is 1.09. The vanes have a thickness distribution defined by a thin NACA aerofoil. As can be seen from the angular distribution **116**, these vanes have a fairly radial leading edge angle of around 0.5 radians. The angular distribution **116** performs most of the turning of the fluid flow in the first 35% of the length of the vanes **112**, with little change thereafter.

FIG. **6A** shows an arrangement **120** of vanes **122** designed according to the new method shown in FIG. **3** in a plane perpendicular to the turbocharger axis **8**. The arrangement **120** comprises 14 vanes **122** arranged evenly around the turbocharger axis **8**.

FIG. **6B** shows the thickness distribution **124** of the vanes **122** shown in FIG. **6A** as a percentage along the length of the vanes **122** (from the leading edge **122a** to the trailing edge **122b**).

FIG. **6C** shows the angular distribution **126** of the vanes **122** shown in FIG. **6A** as a percentage along the length of the vanes **122** (from the leading edge **122a** to the trailing edge **122b**).

In the arrangement **120** of vanes **122**, the ratio of the radius of the trailing edge **122b** of the vanes **122** to the radius of the tip (or leading edge) of the turbine wheel **6** is 1.2. The vanes have a thickness distribution defined by an adjusted

NACA aerofoil having increased thickness at the leading edge **122a** and the trailing edge **122b** (relative to a standard NACA aerofoil).

The increased trailing edge **122b** thickness of the vanes **122** for FOD results in a larger wake than is caused by the vanes **112** shown in FIG. **5A**. However, since the ratio of the radius of the trailing edge **122b** of the vanes **122** to the radius of the tip (or leading edge) of the turbine wheel **6** is increased to 1.2, this vane wake dissipates further from the turbine wheel **6** leading edge than does the wake caused by the vanes **112** shown in FIG. **5A**. Furthermore, the arrangement **120** shown in FIG. **6A** results in a lower static pressure fluctuation at the leading edge of the turbine wheel **6** compared to the arrangement **110** shown in FIG. **5A**. Furthermore, as will be discussed further below, the increases leading edge **122a** thickness increases the tolerance of the arrangement to a range of angles of attack.

The thickness distribution **124** of the vanes **122** shown in FIG. **6A** as a percentage along the length of the vanes **122** (from the leading edge **122a** to the trailing edge **122b**) is also given in Table 1.

The angular distribution **126** of the vanes **122** shown in FIG. **6A** as a percentage along the length of the vanes **122** (from the leading edge **122a** to the trailing edge **122b**) is also given in Table 2.

The x-y co-ordinates of four curves which define the shape and position of one of the vanes **122** shown in FIG. **6A** are given in Tables 3 to 6. The four curves are: a leading edge treatment curve (Table 3); a first side of the vane **122** (Table 4); a trailing edge treatment curve (Table 5); and a second side of the vane **122** (Table 6). The four curves given in Tables 3 to 6 define the shape and position of one of the vanes **122** shown in FIG. **6A** in a plane perpendicular to the turbocharger axis **8**, with the co-ordinates such that the origin coincides with the position of the turbocharger axis **8** (i.e. the turbocharger axis **8** is at x=y=0). It will be appreciated that the other (13) vanes have the same size and shape as that defined by the four curves given in Tables 3 to 6 but are disposed at different positions with respect to the axis. In particular, as stated above, the (14) vanes **122** are arranged evenly around the turbocharger axis **8**. Therefore, the positions of the other (13) vanes can be obtained by rotating the x-y co-ordinates of the four curves given in Tables 3 to 6 about the origin by n*360/14 degrees, where n is an integer between 1 and 13 inclusive.

FIG. **7A** shows an arrangement **130** of vanes **132** designed according to the new method shown in FIG. **4** in a plane perpendicular to the turbocharger axis **8**. The arrangement **130** comprises 14 vanes **132** arranged evenly around the turbocharger axis **8**.

FIG. **7B** shows the thickness distribution **134** of the vanes **132** shown in FIG. **7A** as a percentage along the length of the vanes **132** (from the leading edge **132a** to the trailing edge **132b**).

FIG. **7C** shows the angular distribution **136** of the vanes **132** shown in FIG. **7A** as a percentage along the length of the vanes **132** (from the leading edge **132a** to the trailing edge **132b**).

In the arrangement **130** of vanes **132** shown in FIG. **7A**, the ratio of the radius of the trailing edge **132b** of the vanes **132** to the radius of the tip (or leading edge) of the turbine wheel **6** is 1.14. The vanes **132** have an exponentially decreasing thickness distribution **134**. The vanes **132** have a significantly increased thickness at the leading edge **132a** (relative to a standard NACA aerofoil). In addition, as can be

seen from the angular distribution **136**, the vanes **132** have an angular distribution which is tangential at the leading edge **132a**.

The vanes **132** also have a significantly increased thickness at the trailing edge **132b** (relative to a standard NACA 5 aerofoil). As with the vanes **122** shown in FIG. **6A**, the increased trailing edge **132b** thickness of the vanes **132** in FIG. **7A** results in a larger wake than is caused by the vanes **112** shown in FIG. **5A**. However, since the ratio of the radius of the trailing edge **132b** of the vanes **132** in FIG. **7A** to the radius of the tip (or leading edge) of the turbine wheel **6** is reduced relative to vanes **122** shown in FIG. **6A**, this vane wake does not dissipate before the flow impinges on the turbine wheel **6** leading edge.

As will be described further below, the shape of the vanes **132** shown in FIG. **7A** is such that there is a significant contribution to the variation in static pressure around the leading edge of the turbine wheel **6** having a pitch smaller than the pitch of the vanes **132**. In particular the turbine wheel **6** leading edge static pressure variation has an additional region of low pressure close to the trailing edge **132b** of the vanes **132** which results in a non-vane order pressure fluctuation on the leading edge of the turbine wheel **6**. As a result, the arrangement **130** shown in FIG. **7A** results in a lower static pressure fluctuation at the leading edge of the turbine wheel **6** compared to the arrangement **110** shown in FIG. **5A**. Furthermore, as will be discussed further below, the increases leading edge **132a** thickness increases the tolerance of the arrangement to a range of angles of attack.

The thickness distribution **134** of the vanes **132** shown in FIG. **7A** as a percentage along the length of the vanes **132** (from the leading edge **132a** to the trailing edge **132b**) is also given in Table 7.

The angular distribution **136** of the vanes **132** shown in FIG. **7A** as a percentage along the length of the vanes **132** (from the leading edge **132a** to the trailing edge **132b**) is also given in Table 8.

The x-y co-ordinates of four curves which define the shape and position of one of the vanes **132** shown in FIG. **7A** are given in Tables 9 to 12. The four curves are: a leading edge treatment curve (Table 9); a first side of the vane **132** (Table 10); a trailing edge treatment curve (Table 11); and a second side of the vane **132** (Table 12). The four curves given in Tables 9 to 12 define the shape and position of one of the vanes **132** shown in FIG. **7A** in a plane perpendicular to the turbocharger axis **8**, with the co-ordinates such that the origin coincides with the position of the turbocharger axis **8** (i.e. the turbocharger axis **8** is at $x=y=0$). It will be appreciated that the other (13) vanes have the same size and shape as that defined by the four curves given in Tables 9 to 12 but are disposed at different positions with respect to the axis **8**. In particular, as stated above, the (14) vanes **132** are arranged evenly around the turbocharger axis **8**. Therefore, the positions of the other (13) vanes can be obtained by rotating the x-y co-ordinates of the four curves given in Tables 9 to 12 about the origin by $n \cdot 360/14$ degrees, where n is an integer between 1 and 13 inclusive.

The relative performances of the new inlet vanes described above are now discussed with reference to FIGS. **8A** to **13C**.

FIGS. **8A** to **9C** illustrate the performance of the arrangement **110** of vanes **112** shown in FIG. **5A**. In particular, FIGS. **8A** to **8C** illustrate the performance of the arrangement **110** of vanes **112** shown in FIG. **5A** for an exhaust flow for which the arrangement **110** has been designed and FIGS. **9A** to **9C** illustrate the performance of the arrangement **110** for an exhaust flow for which the arrangement **110** has not

been designed. FIGS. **8A** and **9A** show plots **140**, **150** of flow lines through the arrangement **110**; FIGS. **8B** and **9B** show pressure distributions **142**, **152** through the arrangement **110**; and FIGS. **8C** and **9C** show the same pressure distributions **142**, **152** through the arrangement **110** and, in addition, static pressure distributions **144**, **154** at the leading edge of the turbine wheel **6**.

FIGS. **10A** to **11C** illustrate the performance of the arrangement **120** of vanes **122** shown in FIG. **6A**. In particular, FIGS. **10A** to **10C** illustrate the performance of the arrangement **120** of vanes **122** shown in FIG. **6A** for an exhaust flow for which the arrangement **120** has been designed and FIGS. **11A** to **11C** illustrate the performance of the arrangement **120** for an exhaust flow for which the arrangement **120** has not been designed. FIGS. **10A** and **11A** show plots **160**, **170** of flow lines through the arrangement **120**; FIGS. **10B** and **11B** show pressure distributions **162**, **172** through the arrangement **120**; and FIGS. **10C** and **11C** show the same pressure distributions **162**, **172** through the arrangement **120** and, in addition, static pressure distributions **164**, **174** at the leading edge of the turbine wheel **6**.

FIGS. **12A** to **13C** illustrate the performance of the arrangement **130** of vanes **132** shown in FIG. **7A**. In particular, FIGS. **12A** to **12C** illustrate the performance of the arrangement **130** of vanes **132** shown in FIG. **7A** for an exhaust flow for which the arrangement **130** has been designed and FIGS. **13A** to **13C** illustrate the performance of the arrangement **130** for an exhaust flow for which the arrangement **130** has not been designed. FIGS. **12A** and **13A** show plots **180**, **190** of flow lines through the arrangement **130**; FIGS. **12B** and **13B** show pressure distributions **182**, **192** through the arrangement **130**; and FIGS. **12C** and **13C** show the same pressure distributions **182**, **192** through the arrangement **130** and, in addition, static pressure distributions **184**, **194** at the leading edge of the turbine wheel **6**.

First, consider the performance of the arrangement **110** of vanes **112** shown in FIG. **5A**.

It should be understood that an exhaust flow for which the arrangement **110** has been designed is intended to mean a design point (for example a VG gap as defined by the movable wall member **12**) which corresponds to a particular mass flow. Furthermore, as described above with reference to FIGS. **2** to **4**, any reference (see steps **54**, **76** and **96**) to aligning an angle of the leading edge of the vane with the expected angle of flow into the nozzle ring **12** is intended to mean aligning the leading edge of the vane such that the throat (the region of minimum area in between the vanes) is aligned to the expected angle of flow into the nozzle ring **12** for this design point.

In the examples described herein, the design point (or, equivalently, an exhaust flow for which the arrangements have been designed) is for a flush gap arrangement wherein the VG gap substantially matches a width of a leading edge (or tip) of the turbine wheel **6**. The angle of the exhaust gas as it impinges on the leading edge of the vanes at such a design point is dependent in the geometry of the inlet volute **9** (for example the area and radius of the critical area and the area and radius of the volute exit area, which forms an inlet for the nozzle ring). In the examples described herein, at the (flush gap) design point, at the leading edge of the vanes the gas flow is at approximately 60° to the radial direction.

In the examples described herein, the off-design point corresponds to a smaller VG gap at which the gas flow has overturned and impinges on the leading edge of the vanes at a more radial direction.

As can be seen from FIGS. **8A** and **8B**, at this design point, (where the throat of the nozzle ring is aligned to the

gas flow) there is smooth flow between the vanes 112, with most of the work being done on the fluid in the first 25% of the vanes 112. Thereafter, the vanes 112 generally just act to guide the flow onto the turbine wheel 6. As shown in FIG. 8C, at this design point the static pressure distribution 144 (or forcing function) at the leading edge of the turbine wheel 6 has alternating regions of high pressure 145 (from the flow through the center of the passages between the vanes 112) and regions of low pressure 146 (from the wake of each vane 112 as the flow on either side of the vanes comes together).

As can be seen from FIG. 9A away from the design point, where the throat of the nozzle ring is not well aligned to the gas flow, the flow accelerates around the leading edge 112a of the vanes 112 onto the suction side 112c of the vanes. As can be seen from FIG. 9B, this causes an increased depression region 153 to develop on the suction side 112c of the vanes 112. In turn, this results in a significant increase in the static pressure distribution 154 (or forcing function) at the leading edge of the turbine wheel 6. The static pressure distribution 154 has alternating regions of high pressure 155 (from the flow through the center of the passages between the vanes 112) and increased regions of low pressure 156 (from the wake of each vane 112 as the flow on either side of the vanes comes together).

Next, consider the performance of the arrangement 120 of vanes 122 shown in FIG. 6A.

As can be seen from FIGS. 10A and 10B, at the design point, (where the throat of the nozzle ring is aligned to the gas flow) the increased leading edge 122a and trailing edge 122b thicknesses of the vanes 122 has little effect on the smooth flow between the vanes 122 (as compared to the flow between the vanes 112 shown in FIGS. 8A and 8B). As shown in FIG. 10C, at this design point the static pressure distribution 164 (or forcing function) at the leading edge of the turbine wheel 6 also has alternating regions of high pressure 165 (from the flow through the center of the passages between the vanes 122) and regions of low pressure 166 (from the wake of each vane 122 as the flow on either side of the vanes comes together). However, since the ratio of the radius of the trailing edge 122b of the vanes 122 to the radius of the tip (or leading edge) of the turbine wheel 6 is increased (relative to the arrangement 110 shown in FIGS. 8) to 1.2, the vane wake dissipates further from the turbine wheel 6 leading edge. As a result, there is smaller amplitude difference between the regions of high pressure 165 and regions of low pressure 166, which results in a lower amplitude of static pressure 164 fluctuation at the leading edge of the turbine wheel 6 compared to the arrangement 110 shown in FIG. 5A.

As can be seen from FIG. 11A away from the design point, where the throat of the nozzle ring is not well aligned to the gas flow, again the flow accelerates around the leading edge 122a of the vanes 122 onto the suction side 122c of the vanes 122. However, as can be seen from FIG. 11B, although this causes an increased depression region 173 to develop on the suction side 122c of the vanes 122, this increased depression region 173 off design point is significantly reduced relative to the corresponding increased pressure region 153 which develops off design point for the arrangement 110 of FIG. 5A (see FIG. 9B). It is thought that this is due to the increased, more bulbous leading edge 122a of these vanes 122, which allow the flow 170 (see FIG. 11A) to better follow the suction side 122c of the vanes 122 after accelerating around the leading edge 122a.

In turn, although there will be an increase in the static pressure distribution 174 (or forcing function) at the leading edge of the turbine wheel 6 (relative to the design point, see

FIG. 10C), this increase is significantly reduced relative to the corresponding increase experienced with the arrangement 110 of FIG. 5A (see FIGS. 8C and 9C). The static pressure distribution 174 has alternating regions of high pressure 175 (from the flow through the center of the passages between the vanes 122) and increased regions of low pressure 176 (from the wake of each vane 122 as the flow on either side of the vanes comes together). Furthermore, since the ratio of the radius of the trailing edge 122b of the vanes 122 to the radius of the tip (or leading edge) of the turbine wheel 6 is increased (relative to the arrangement 110 shown in FIGS. 9) to 1.2, the vane wake dissipates further from the turbine wheel 6 leading edge. As a result, there is smaller amplitude difference between the regions of high pressure 175 and regions of low pressure 176, which results in a lower amplitude of static pressure 174 fluctuation at the leading edge of the turbine wheel 6 compared to the arrangement 110 shown in FIG. 5A.

Next, consider the performance of the arrangement 130 of vanes 132 shown in FIG. 7A.

As can be seen from FIGS. 12A and 12B, at the design point, (where the throat of the nozzle ring is aligned to the gas flow) the increased leading edge 132a and trailing edge 132b thicknesses of the vanes 132 has little effect on the smooth flow between the vanes 122 (as compared to the flow between the vanes 112 shown in FIGS. 8A and 8B).

As shown in FIG. 12C, at this design point the static pressure distribution 184 (or forcing function) at the leading edge of the turbine wheel 6 also has alternating regions of high pressure (from the flow through the center of the passages between the vanes 132) and regions of low pressure (from the wake of each vane 132 as the flow on either side of the vanes comes together). However, due to the specific and rather unusual shape of these vanes 132, the two separate low pressure regions (which arise from the disturbance caused by the vanes 132) are formed in the pitch of the vanes 132. Therefore, rather than just a static pressure distribution 184 which varies with a smaller to that of the vanes 132 (for example around half the pitch). With 14 vanes 132, one may expect a dominant contribution to the static pressure distribution 184 around the circumference of the turbine wheel 6 to vary with 14 peaks and 14 troughs. This may be referred to a 14th order or vane order oscillation. However, due to the specific and rather unusual shape of these vanes, there is also a significant contribution to the static pressure distribution around the circumference of the turbine wheel 6 to vary with 28 peaks and 28 troughs. This may be referred to a 28th order or non-vane order oscillation.

This can be seen more clearly in FIG. 14, which shows the static pressure variation 200, 202 (averaged over the axial direction) over an angular region of the turbine wheel 6 corresponding to a single vane 112, 132 for the arrangements 110, 130 shown in FIGS. 5A and 7A respectively. These averaged static pressure variations 200, 202 are equivalent to the static pressure distributions 144, 184 shown in FIGS. 8C and 12C by averaging in the axial directions 148, 188 indicated in those Figures.

It is clear from the averaged static pressure variations 200, 202 that as a result of this excitation of the non-vane order oscillations, the overall amplitude of the static pressure variations has been reduced (the amplitude of variation 202 being less than that of the variation 200).

It is thought that this separation of the wake caused by the shape of the vanes 132 shown in FIG. 7A is due the flow experiencing different losses on the suction side 132c and pressure side 132d of the vanes 132. That is, rather than the

pressure of the flow on the opposite sides of the vane being equal at the trailing edge 132b of the vanes 132 (as would be the case for a conventional aerofoil shape) there is a pressure differential across these flows.

It is thought that the separation of the wake is caused by a combination of: (a) an increased (more bulbous) thickness of the leading edge 132a of the vanes 132; (b) a rapid reduction in the thickness distribution, in combination with (c) the leading edge 132a of the vanes 132 being directed more tangentially. As the gas flows over the leading edge 132a onto the suction side 132c of the vane 132, in contrast to a traditional aerofoil shape which would then have a thicker portion to slowly guide the flow along the suction side, the suction side 132c of these vanes 132 suddenly falls away, making it difficult for the flow to follow it and causing separation of the flow from the suction side 132c. As can be seen from FIG. 12A, the bulk of this flow is still quite well guided onto the turbine wheel 6, at least partially by the higher pressure flow through a central portion of the passageways between the vanes 132. However, there is sufficient separation to cause a double wake that excites the non-vane order oscillations on the static pressure distribution 184 (also referred to herein as a forcing function).

This effect is thought to be enhanced by the fact that the leading edges 132a of the vanes 132 are turned more tangentially (which may, for example, be in order to close the throat of the nozzle despite the vanes being of reduced length due to packing constraints). However, it will be appreciated that this enhancement may not be necessary.

As can be seen from FIG. 13A away from the design point, where the throat of the nozzle ring is not well aligned to the gas flow, again the flow accelerates around the leading edge 132a of the vanes 132 onto the suction side 132c of the vanes 132. As can be seen from the flow lines through the arrangement 130 (see FIG. 13A), off design point the flow is not as well guided onto the turbine wheel 6. However, due to the excitation of non-vane order oscillations, the variation in the static pressure distribution 194 (or forcing function) at the leading edge of the turbine wheel 6 is still significantly reduced relative to the corresponding static pressure distribution 154 experienced with the arrangement 110 of FIG. 5A (see FIG. 9C). Again, it is thought that the increased, more bulbous leading edge 132a of these vanes 132, allows the bulk of flow 190 to better follow the suction side 132c of the vanes 132 after accelerating around the leading edge 132a.

The new arrangements 120, 130 of vanes 122, 132 shown in FIGS. 6A and 7A both have increased dimensions at the leading edge (relative to known arrangements).

The use of such a bulbous or blunt leading edge is contrary to the existing teaching in the art, which would prompt the skilled person to select a smaller radius of curvature at the leading edge or the vanes in order to achieve better separation of the flow over the vanes (in turn, increasing the efficiency of the turbine). However, the inventors of the present disclosure have realized that for a variable geometry turbine, the angle of attack of the flow of fluid over the vanes is dependent on the position of the movable wall member 12 (i.e. the VG gap). By increasing the dimensions of the vanes 122, 132 at the leading edge the arrangements 120, 130 of vanes 122, 132 shown in FIGS. 6A and 7A will operate with a relatively high efficiency over a larger range of angles of attack (and therefore, equivalently, over a larger range of positions of the movable wall member 12 or VG gaps). In addition, and perhaps of more relevance, the arrangements 120, 130 of vanes 122, 132 shown in FIGS. 6A and 7A will maintain the amplitude of the forcing

function relatively low over a significantly larger range of positions of the movable wall member. In turn this reduces high cycle fatigue caused by large forcing functions.

Although the general "envelope" shape of each vane described herein can be described by a thickness distribution from the leading edge to the trailing edge, as described above, the actual thickness of the vanes is reduced relative to this thickness distribution at the leading and trailing edges by the (elliptical) end treatments. FIG. 15 shows the actual thicknesses 210, 212, 214 of the vanes 112, 122, 132 shown in FIGS. 5A, 6A and 7A respectively, as a percentage of the vane length. The actual thickness of the vanes 122 shown in FIG. 6A, as a percentage of the vane length, is given in Table 13 and the actual thickness of the vanes 132 shown in FIG. 7A, as a percentage of the vane length, is given in Table 14. It can be seen that even with the elliptical end treatments at the leading and trailing edges the new vanes 122, 132 shown in FIGS. 6A and 7A have a significantly increased thickness (relative to the vanes 112 shown in FIG. 5A) at the leading and trailing edges.

The perpendicular thickness of the new vanes 122 shown in FIG. 6A 5% along the length of the vane from the leading edge is around 60% of the maximum perpendicular thickness of the vane 122. The perpendicular thickness of the new vanes 132 shown in FIG. 7A 5% along the length of the vane from the leading edge is around 85% of the maximum perpendicular thickness of the vane 132. In contrast, the perpendicular thickness of the known vanes 112 shown in FIG. 5A 5% along the length of the vane from the leading edge is around 42% of the maximum perpendicular thickness of the vane 122. At least some increased tolerance to variation in angle of attack is expected for a vanes having a perpendicular thickness 5% along the length of the vane from the leading edge of at least 50% of the maximum perpendicular thickness of the vane.

The use of a larger, more bulbous trailing edge profile with respect to known vanes is advantageous, since it increases the foreign object damage (FOD) tolerance of the vanes.

The perpendicular thickness of the new vanes 122 shown in FIG. 6A 95% along the length of the vane from the leading edge is around 46% of the maximum perpendicular thickness of the vane 122. The perpendicular thickness of the new vanes 132 shown in FIG. 7A 95% along the length of the vane from the leading edge is around 63% of the maximum perpendicular thickness of the vane 132. In contrast, the perpendicular thickness of the known vanes 112 shown in FIG. 5A 95% along the length of the vane from the leading edge is around 26% of the maximum perpendicular thickness of the vane 122. At least some increased tolerance to FOD is expected for a vanes having a perpendicular thickness 95% along the length of the vane from the leading edge of at least 40% of the maximum perpendicular thickness of the vane.

TABLE 1

The thickness distribution of the vanes shown in FIG. 6A as a percentage along the length of the vanes (from the leading edge to the trailing edge).	
% OF VANE LENGTH	Thickness [mm]
0	1.28075891
4.16666667	1.5142213
8.33333333	1.74503479
12.5	1.97319894

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TABLE 1-continued

The thickness distribution of the vanes shown in FIG. 6A as a percentage along the length of the vanes (from the leading edge to the trailing edge).	
% OF VANE LENGTH	Thickness [mm]
16.66666667	2.19389963
20.83333333	2.38563096
25	2.52329323
29.16666667	2.59077096
33.33333333	2.59465697
37.5	2.54315425
41.66666667	2.44712891
45.83333333	2.32423919
50	2.19270031
54.16666667	2.07016004
58.33333333	1.96276142
62.5	1.86594117
66.66666667	1.77472852
70.83333333	1.68415274
75	1.59020486
79.16666667	1.49381224
83.33333333	1.39748158
87.5	1.30364505
91.66666667	1.21343513
95.83333333	1.12688631
100	1.0439986

TABLE 2

The angular distribution of the vanes shown in FIG. 6A as a percentage along the length of the vanes (from the leading edge to the trailing edge).	
% OF VANE LENGTH	Angle Distribution in Radians
0	0.837758
4.16666667	0.937494785
8.33333333	1.01702377
12.5	1.07739489
16.66666667	1.12068936
20.83333333	1.1513081
25	1.17393104
29.16666667	1.19070175
33.33333333	1.20151587
37.5	1.20631788
41.66666667	1.20642288
45.83333333	1.20398422
50	1.20116729
54.16666667	1.19985451
58.33333333	1.19997534
62.5	1.20063531
66.66666667	1.20101195
70.83333333	1.2009828
75	1.20080709
79.16666667	1.20071093
83.33333333	1.20071359
87.5	1.20076252
91.66666667	1.20080591
95.83333333	1.20081555
100	1.20079

TABLE 3

A first curve defining a portion of the shape and position of one of the vanes shown in FIG. 6A.	
x	y
53.1984	2.48845
53.2522	2.44078
53.307	2.39646
53.3627	2.3556

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TABLE 3-continued

A first curve defining a portion of the shape and position of one of the vanes shown in FIG. 6A.		
	x	y
5	53.4189	2.31833
	53.4756	2.28472
	53.5325	2.25486
	53.5894	2.22878
	53.6462	2.20653
10	53.7026	2.18811
	53.7585	2.17354
	53.8136	2.16279
	53.8679	2.15582
	53.9211	2.15258
15	53.9731	2.15301
	54.0238	2.15702
	54.0729	2.16452
	54.1205	2.1754
	54.1663	2.18955
20	54.2103	2.20682
	54.2524	2.22709
	54.2924	2.25022
	54.3304	2.27607
	54.3663	2.30447
25	54.3999	2.33529
	54.4313	2.36837
	54.4604	2.40357
	54.4872	2.44073
	54.5117	2.47972
30	54.5338	2.5204
	54.5535	2.56264
	54.5707	2.60632
	54.5855	2.65131
	54.5979	2.69751
35	54.6077	2.74481
	54.615	2.79313
	54.6198	2.84236
	54.622	2.89244
	54.6217	2.94329
40	54.6187	2.99484
	54.6131	3.04701
	54.6049	3.09976
	54.5941	3.15303
	54.5806	3.20674
45	54.5644	3.26084
	54.5456	3.31528
	54.5241	3.36997
	54.5001	3.42487
	54.4735	3.4799

TABLE 4

A second curve defining a portion of the shape and position of one of the vanes shown in FIG. 6A.		
	x	y
50	54.4735	3.4799
	54.4619	3.50274
	54.4464	3.53347
	54.4271	3.57213
	54.404	3.61873
	54.3771	3.6733
	54.3466	3.73588
	54.3125	3.80651
	54.2748	3.8852
	54.2338	3.97198
60	54.1894	4.06685
	54.1418	4.1698
	54.0909	4.28086
	54.0369	4.40004
	53.9798	4.52729
	53.9196	4.66252
	53.8562	4.80562
	53.7895	4.95645
	53.7195	5.11487

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TABLE 4-continued

A second curve defining a portion of the shape and position of one of the vanes shown in FIG. 6A.	
x	y
53.6459	5.28066
53.5687	5.45359
53.4877	5.63339
53.4026	5.81977
53.3133	6.01246
53.2196	6.21111
53.1213	6.41535
53.0181	6.62488
52.91	6.83936
52.7967	7.0585
52.6784	7.28208
52.555	7.5099
52.4267	7.74179
52.2934	7.9775
52.155	8.21674
52.0117	8.45929
51.8634	8.70485
51.71	8.95309
51.5517	9.20371
51.3886	9.45641
51.2206	9.71087
51.0481	9.96677
50.8712	10.2238
50.6901	10.4818
50.5053	10.7403
50.3168	10.9991
50.1251	11.2579
49.9306	11.5166
49.7335	11.775
49.5345	12.0328
49.3339	12.29
49.132	12.5464
48.9292	12.8017
48.7256	13.0559
48.5214	13.3086
48.3167	13.5598
48.1117	13.8091
47.9064	14.0564
47.701	14.3014
47.4957	14.5439
47.2906	14.7838
47.0858	15.0206
46.8815	15.2543
46.6778	15.4846
46.4749	15.7113
46.273	15.934
46.0722	16.1528
45.8728	16.3672
45.6751	16.5774
45.4792	16.783
45.2856	16.984
45.0944	17.1803
44.9059	17.3718
44.7203	17.5584
44.5379	17.7399
44.3589	17.9164
44.1835	18.0877
44.012	18.2537
43.8446	18.4144
43.6814	18.5697
43.5228	18.7195
43.3689	18.8637
43.2198	19.0024
43.0759	19.1353
42.9371	19.2625
42.8038	19.384
42.6761	19.4996
42.5542	19.6093
42.4381	19.7131
42.3281	19.8109
42.2243	19.9028
42.1269	19.9886
42.0359	20.0683
41.9514	20.142
41.8737	20.2096

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TABLE 4-continued

A second curve defining a portion of the shape and position of one of the vanes shown in FIG. 6A.	
x	y
41.8027	20.271
41.7386	20.3264
41.6815	20.3755
41.6314	20.4185
41.5884	20.4554
41.5525	20.486
41.5239	20.5104
41.5025	20.5287
41.4883	20.5407

TABLE 5

A third curve defining a portion of the shape and position of one of the vanes shown in FIG. 6A.	
x	y
41.4883	20.5407
41.4609	20.5626
41.4322	20.5826
41.4023	20.6008
41.3713	20.617
41.3394	20.6312
41.3066	20.6433
41.2732	20.6533
41.2392	20.6611
41.2048	20.6667
41.1702	20.6701
41.1354	20.6712
41.1007	20.6701
41.0661	20.6668
41.0318	20.6612
40.998	20.6535
40.9648	20.6436
40.9323	20.6315
40.9007	20.6174
40.87	20.6013
40.8404	20.5833
40.8121	20.5634
40.7851	20.5417
40.7595	20.5183
40.7355	20.4934
40.7131	20.467
40.6924	20.4391
40.6736	20.4101
40.6566	20.3799
40.6415	20.3487
40.6285	20.3166
40.6175	20.2838
40.6086	20.2503
40.6018	20.2164
40.5972	20.1821
40.5947	20.1477
40.5944	20.1131
40.5962	20.0787
40.6003	20.0444
40.6065	20.0105
40.6148	19.9771
40.6251	19.9444
40.6376	19.9123
40.652	19.8812
40.6684	19.851
40.6866	19.822
40.7067	19.7942
40.7284	19.7677
40.7518	19.7427

TABLE 6

A fourth curve defining a portion of the shape and position of one of the vanes shown in FIG. 6A.

x	y
40.7518	19.7427
40.7647	19.7299
40.7841	19.7104
40.8101	19.6843
40.8426	19.6515
40.8815	19.6122
40.9269	19.5663
40.9786	19.5138
41.0366	19.4547
41.1008	19.3891
41.171	19.317
41.2472	19.2383
41.3293	19.1532
41.4171	19.0617
41.5105	18.9637
41.6093	18.8594
41.7135	18.7487
41.8229	18.6317
41.9372	18.5085
42.0564	18.3791
42.1802	18.2436
42.3085	18.102
42.4411	17.9544
42.5777	17.8008
42.7183	17.6415
42.8626	17.4763
43.0104	17.3055
43.1615	17.1291
43.3156	16.9473
43.4727	16.7601
43.6325	16.5677
43.7947	16.3703
43.9593	16.1679
44.126	15.9608
44.2946	15.749
44.4649	15.5328
44.6367	15.3123
44.8099	15.0877
44.9842	14.8591
45.1596	14.6269
45.3357	14.391
45.5123	14.1517
45.6893	13.9091
45.8663	13.6634
46.043	13.4147
46.2194	13.1633
46.395	12.9093
46.5697	12.6529
46.7431	12.3943
46.915	12.1337
47.0851	11.8713
47.2531	11.6074
47.4187	11.342
47.5816	11.0755
47.7419	10.8082
47.8994	10.5402
48.0542	10.272
48.2064	10.0038
48.3563	9.73608
48.5041	9.46916
48.6499	9.20337
48.7939	8.93909
48.9362	8.67659
49.0772	8.41622
49.217	8.15835
49.3558	7.90329
49.4938	7.65137
49.6311	7.40292
49.7677	7.15824
49.9038	6.91762
50.0393	6.68135
50.1743	6.44977
50.3087	6.22315
50.4426	6.00177
50.576	5.78596

TABLE 6-continued

A fourth curve defining a portion of the shape and position of one of the vanes shown in FIG. 6A.

x	y
50.7087	5.57601
50.841	5.37217
50.9725	5.17462
51.103	4.98346
51.2322	4.79878
51.3599	4.62065
51.4858	4.44911
51.6096	4.28426
51.731	4.12617
51.8497	3.97492
51.9654	3.83057
52.0779	3.6932
52.1868	3.5629
52.2918	3.43976
52.3926	3.32385
52.489	3.21521
52.5806	3.11391
52.6673	3.02003
52.7486	2.93362
52.8244	2.8547
52.8943	2.78323
52.9581	2.7192
53.0155	2.66255
53.0663	2.61324
53.1102	2.57124
53.1469	2.53648
53.1764	2.50891
53.1984	2.48845

TABLE 7

The thickness distribution of the vanes shown in FIG. 7A as a percentage along the length of the vanes (from the leading edge to the trailing edge).

% OF VANE LENGTH	Thickness [mm]
0	3
4.166666671	2.68002698
8.333333329	2.47462239
12.5	2.32043209
16.66666671	2.19712996
20.83333329	2.09507891
25	2.00880635
29.16666671	1.93483086
33.33333329	1.87084379
37.5	1.81510879
41.66666671	1.76639048
45.83333329	1.72371248
50	1.68631667
54.16666671	1.65357658
58.33333329	1.62500412
62.5	1.60015877
66.66666671	1.57870697
70.83333329	1.56033635
75	1.5447882
79.16666671	1.53184531
83.33333329	1.52130155
87.5	1.51299153
91.66666671	1.50676059
95.83333329	1.50246962
100	1.5

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TABLE 8

The angular distribution of the vanes shown in FIG. 7A as a percentage along the length of the vanes (from the leading edge to the trailing edge).	
% OF VANE LENGTH	Angle Distribution in Radians
0	1.23685
4.16666665	1.24065031
8.333333354	1.2418039
12.5	1.24031078
16.66666665	1.23617095
20.83333335	1.22938441
25	1.21999442
29.16666665	1.2087142
33.33333335	1.19678444
37.5	1.18546009
41.66666665	1.17599611
45.83333335	1.16964102
50	1.16687287
54.16666665	1.16667795
58.33333335	1.1678718
62.5	1.16926995
66.66666646	1.1698859
70.83333354	1.16978665
75	1.16938817
79.16666646	1.1690462
83.33333354	1.16883979
87.5	1.16876897
91.66666646	1.16883374
95.83333354	1.16903408
100	1.16937

TABLE 9

A first curve defining a portion of the shape and position of one of the vanes shown in FIG. 7A.	
x	y
48.9619	2.1136
49.0142	1.95703
49.0721	1.80154
49.1351	1.6479
49.2031	1.49689
49.2756	1.34926
49.3524	1.20576
49.4331	1.06711
49.5174	0.934032
49.6048	0.807213
49.6949	0.687327
49.7874	0.575004
49.8818	0.470845
49.9776	0.375414
50.0745	0.289204
50.172	0.212652
50.2696	0.146146
50.3668	0.090032
50.4633	0.044607
50.5586	0.010121
50.6521	-0.01323
50.7434	-0.02529
50.8322	-0.02598
50.9178	-0.01524
51	0.006897
51.0782	0.040369
51.152	0.085049
51.2211	0.140753
51.285	0.207243
51.3435	0.284223
51.396	0.371344
51.4424	0.4682
51.4823	0.574333
51.5155	0.689234
51.5417	0.812344
51.5609	0.943054
51.5727	1.08072

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TABLE 9-continued

A first curve defining a portion of the shape and position of one of the vanes shown in FIG. 7A.		
	x	y
5	51.5771	1.22465
	51.574	1.37414
	51.5634	1.5284
	51.5452	1.68662
10	51.5196	1.84793
	51.4866	2.01144
	51.4464	2.17623
	51.3992	2.34138
	51.3451	2.50594
15	51.2846	2.66899
	51.2179	2.8296
	51.1454	2.98686

TABLE 10

A second curve defining a portion of the shape and position of one of the vanes shown in FIG. 7A.		
	x	y
20		
25	51.1454	2.98686
	51.1307	3.017
	51.1128	3.05392
	51.0916	3.09755
	51.0671	3.14786
	51.0393	3.2048
30	51.0084	3.26832
	50.9742	3.33836
	50.9368	3.41486
	50.8962	3.49773
	50.8525	3.58692
	50.8056	3.68232
35	50.7556	3.78385
	50.7024	3.8914
	50.6461	4.00487
	50.5866	4.12413
	50.524	4.24907
	50.4584	4.37957
40	50.3896	4.51548
	50.3176	4.65667
	50.2426	4.80298
	50.1645	4.95427
	50.0832	5.11038
	49.9989	5.27113
	49.9114	5.43635
45	49.8207	5.60586
	49.727	5.77948
	49.6301	5.95699
	49.53	6.13818
	49.4268	6.32286
	49.3204	6.51081
50	49.211	6.70181
	49.0984	6.8956
	48.9827	7.09199
	48.864	7.29073
	48.7422	7.49157
	48.6175	7.69429
	48.4899	7.89864
55	48.3595	8.10438
	48.2264	8.3113
	48.0906	8.51917
	47.9524	8.72776
	47.8117	8.93685
60	47.6689	9.14623
	47.524	9.35568
	47.3772	9.56504
	47.2287	9.77411
	47.0788	9.98273
	46.9276	10.1908
	46.7753	10.3981
65	46.622	10.6046
	46.468	10.8102

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TABLE 10-continued

A second curve defining a portion of the shape and position of one of the vanes shown in FIG. 7A.		
x	y	
46.3134	11.0147	
46.1584	11.2181	
46.003	11.4202	
45.8475	11.6209	
45.692	11.82	
45.5366	12.0175	
45.3814	12.2131	
45.2266	12.4068	
45.0723	12.5983	
44.9185	12.7875	
44.7656	12.9743	
44.6135	13.1585	
44.4624	13.34	
44.3125	13.5184	
44.1639	13.6939	
44.0168	13.8661	
43.8714	14.0349	
43.7277	14.2003	
43.5861	14.3621	
43.4466	14.5201	
43.3093	14.6744	
43.1745	14.8247	
43.0424	14.971	
42.9129	15.1132	
42.7864	15.2512	
42.663	15.385	
42.5427	15.5144	
42.4258	15.6393	
42.3124	15.7598	
42.2026	15.8757	
42.0966	15.987	
41.9945	16.0935	
41.8963	16.1954	
41.8024	16.2924	
41.7126	16.3846	
41.6272	16.4719	
41.5463	16.5542	
41.4699	16.6316	
41.3982	16.704	
41.3313	16.7713	
41.2692	16.8335	
41.212	16.8906	
41.1598	16.9426	
41.1126	16.9895	
41.0706	17.0311	
41.0337	17.0676	
41.002	17.0989	
40.9756	17.1249	
40.9545	17.1457	
40.9386	17.1613	
40.9282	17.1716	

TABLE 11

A third curve defining a portion of the shape and position of one of the vanes shown in FIG. 7A.		
x	y	
40.9282	17.1716	
40.8915	17.2053	
40.8527	17.2366	
40.8119	17.2653	
40.7694	17.2912	
40.7254	17.3143	
40.6799	17.3344	
40.6333	17.3515	
40.5857	17.3654	
40.5374	17.3762	
40.4885	17.3837	
40.4393	17.388	
40.39	17.389	

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TABLE 11-continued

A third curve defining a portion of the shape and position of one of the vanes shown in FIG. 7A.		
x	y	
40.3407	17.3868	
40.2918	17.3812	
40.2434	17.3724	
40.1958	17.3605	
40.149	17.3454	
40.1034	17.3272	
40.0591	17.3061	
40.0163	17.282	
39.9752	17.2552	
39.936	17.2258	
39.8987	17.1938	
39.8637	17.1594	
39.8309	17.1229	
39.8006	17.0842	
39.7729	17.0437	
39.7479	17.0015	
39.7256	16.9577	
39.7062	16.9126	
39.6897	16.8664	
39.6762	16.8192	
39.6658	16.7713	
39.6585	16.7229	
39.6543	16.6742	
39.6532	16.6253	
39.6553	16.5765	
39.6605	16.528	
39.6688	16.48	
39.6802	16.4327	
39.6946	16.3863	
39.7119	16.341	
39.7322	16.297	
39.7552	16.2544	
39.7809	16.2134	
39.8093	16.1743	
39.8401	16.137	
39.8733	16.1019	

TABLE 12

A fourth curve defining a portion of the shape and position of one of the vanes shown in FIG. 7A.		
x	y	
39.8733	16.1019	
39.8835	16.0919	
39.8988	16.0767	
39.9192	16.0565	
39.9447	16.0312	
39.9752	16.0007	
40.0108	15.9652	
40.0514	15.9246	
40.0969	15.879	
40.1472	15.8284	
40.2024	15.7727	
40.2623	15.7121	
40.3268	15.6464	
40.3958	15.5759	
40.4694	15.5004	
40.5473	15.4201	
40.6294	15.3349	
40.7158	15.245	
40.8061	15.1502	
40.9004	15.0508	
40.9985	14.9466	
41.1003	14.8379	
41.2056	14.7246	
41.3143	14.6067	
41.4262	14.4845	
41.5413	14.3578	
41.6594	14.2269	
41.7803	14.0916	

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TABLE 12-continued

A fourth curve defining a portion of the shape and position of one of the vanes shown in FIG. 7A.	
x	y
41.9038	13.9523
42.0299	13.8088
42.1583	13.6613
42.2889	13.5099
42.4216	13.3547
42.5561	13.1958
42.6923	13.0333
42.8301	12.8672
42.9693	12.6977
43.1097	12.5249
43.2512	12.3489
43.3937	12.1699
43.537	11.9879
43.6809	11.8032
43.8253	11.6157
43.9701	11.4259
44.1152	11.2336
44.2603	11.0392
44.4053	10.8429
44.55	10.6447
44.6944	10.445
44.8381	10.2438
44.981	10.0414
45.123	9.83784
45.2637	9.63342
45.4031	9.42827
45.541	9.2226
45.677	9.01653
45.8111	8.81026
45.9431	8.60395
46.0727	8.39773
46.2	8.19172
46.3246	7.98611
46.4466	7.78102
46.5658	7.57663
46.6822	7.37311
46.7956	7.17063
46.9062	6.96939
47.0136	6.76958
47.1181	6.5714
47.2195	6.37503
47.3177	6.18069
47.4129	5.98856
47.505	5.79885
47.5941	5.61178
47.68	5.42754
47.7629	5.24633
47.8428	5.06835
47.9196	4.89382
47.9935	4.72293
48.0644	4.55587
48.1323	4.39282
48.1974	4.23399
48.2596	4.07955
48.3189	3.92968
48.3755	3.78456
48.4292	3.64435
48.4803	3.50922
48.5286	3.37932
48.5743	3.25481
48.6173	3.13582
48.6577	3.02248
48.6956	2.91494
48.7309	2.8133
48.7638	2.71769
48.7941	2.62821
48.8221	2.54497
48.8476	2.46806
48.8708	2.39757
48.8916	2.33358
48.9102	2.27618
48.9264	2.22542

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TABLE 12-continued

A fourth curve defining a portion of the shape and position of one of the vanes shown in FIG. 7A.	
x	y
48.9405	2.18136
48.9523	2.14407
48.9619	2.1136

TABLE 13

The actual thickness of the vanes shown in FIG. 6A as a percentage along the length of the vanes (from the leading edge to the trailing edge), including the leading and trailing edges by the (elliptical) end treatments.		
	% OF VANE LENGTH	Thickness [mm]
5	0	0
	0.564971751	0.6497
	1.129943503	0.8973
	1.694915254	1.0733
	2.259887006	1.2093
	2.824858757	1.3182
10	3.389830508	1.4066
	4.166666667	1.5142213
	5.875706215	1.6152
	8.333333333	1.74503479
	12.5	1.97319894
	16.66666667	2.19389963
	20.83333333	2.38563096
15	25	2.52329323
	29.16666667	2.59077096
	33.33333333	2.59465697
	37.5	2.54315425
20	41.66666667	2.44712891
	45.83333333	2.32423919
	50	2.19270031
	54.16666667	2.07016004
	58.33333333	1.96276142
	62.5	1.86594117
	66.66666667	1.77472852
	70.83333333	1.68415274
25	75	1.59020486
	79.16666667	1.49381224
	83.33333333	1.39748158
	87.5	1.30364505
	91.66666667	1.21343513
	95.83333333	1.12688631
30	97.64124294	1.0859
	98.20621469	1.0381
	98.77118644	0.9052
	99.33615819	0.6331
35	100	0

TABLE 14

The actual thickness of the vanes shown in FIG. 7A as a percentage along the length of the vanes (from the leading edge to the trailing edge), including the leading and trailing edges by the (elliptical) end treatments.		
	% OF VANE LENGTH	Thickness [mm]
55	0	0
	0.657894737	0.7981
	1.315789474	1.1109
	1.973684211	1.3399
	2.631578947	1.5237
	3.289473684	1.6767
	3.947368421	1.8068
60	5.263157895	2.0145
	6.578947368	2.1675

TABLE 14-continued

The actual thickness of the vanes shown in FIG. 7A as a percentage along the length of the vanes (from the leading edge to the trailing edge), including the leading and trailing edges by the (elliptical) end treatments.

% OF VANE LENGTH	Thickness [mm]
7.894736842	2.2759
9.210526316	2.3443
10.52631579	2.3747
11.65657895	2.3516
12.5	2.32043209
16.66666671	2.19712996
20.83333329	2.09507891
25	2.00880635
29.16666671	1.93483086
33.33333329	1.87084379
37.5	1.81510879
41.66666671	1.76639048
45.83333329	1.72371248
50	1.68631667
54.16666671	1.65357658
58.33333329	1.62500412
62.5	1.60015877
66.66666671	1.57870697
70.83333329	1.56033635
75	1.5447882
79.16666671	1.53184531
83.33333329	1.52130155
87.5	1.51299153
91.66666671	1.50676059
95.83333329	1.50246962
97.36842105	1.4933
98.02631579	1.442
98.68421053	1.3395
99.34210526	1.1708
100	0

While specific embodiments of the disclosure have been described above, it will be appreciated that the disclosure may be practiced otherwise than as described. The descriptions above are intended to be illustrative, not limiting. Thus it will be apparent to one skilled in the art that modifications may be made to the disclosure as described without departing from the scope of the claims set out below.

The invention claimed is:

1. A variable geometry turbine comprising:

- a turbine housing defining an inlet and an outlet;
 - a turbine wheel rotatably mounted in the turbine housing between the inlet and the outlet such that the turbine wheel can rotate about an axis;
 - a movable wall member mounted in the housing so as to be movable relative to the housing between at least a first position and a second position, the movable wall member partially defining an inlet passageway between the inlet and the turbine wheel, the inlet passageway being radially outboard of the turbine wheel, a dimension of the inlet passageway being dependent on a position of the movable wall member relative to the housing; and
 - a plurality of vanes extending across the inlet passageway, the vanes being circumferentially spaced;
- wherein in cross section each of the vanes has an elongate shape extending from a leading edge which is closer to the inlet to a trailing edge which is closer to the turbine wheel and wherein a perpendicular thickness of the vane 5% along a length of the vane from the leading edge is at least 50% of a maximum perpendicular thickness of the vane; and

wherein the vanes are arranged so as to produce a double wake variation in a static pressure around a circumference of the turbine wheel.

- 2. The variable geometry turbine of claim 1 wherein a perpendicular thickness of the vane 95% along the length of the vane from the leading edge is at least 40% of the maximum perpendicular thickness of the vane.
- 3. The variable geometry turbine of claim 1 wherein the leading edge of the vanes is provided with an elliptical end treatment having a ratio of a major axis to a minor axis of at least 1.5.
- 4. The variable geometry turbine of claim 1 wherein the vanes have a shape at least partially defined by a thickness distribution that exponentially reduces from the leading edge to the trailing edge and having an end treatment at each of the leading and trailing edges.
- 5. The variable geometry turbine of claim 1 wherein the vanes have a shape at least partially defined by an angular distribution that is more tangential at the leading edge than the trailing edge.
- 6. A movable wall member for use in the variable geometry turbine of claim 1.
- 7. A method for designing vanes for the variable geometry turbine of claim 1, the method comprising:
 - selecting a thickness distribution; and
 - applying an edge treatment to each of a leading edge and a trailing edge, the edge treatment for the leading edge being elliptical in cross-section, having a ratio between a minor length and a major length of 1.5 or more;
- wherein a perpendicular thickness of a resultant vane 5% along the length of the vane from the leading edge is at least 50% of a maximum perpendicular thickness of the vane.

8. The method of claim 7 wherein the selection of the thickness distribution and the application of the edge treatment to each of the leading edge and trailing edge is such that a perpendicular thickness of the resultant vane 95% along the length of the vane from the leading edge is at least 40% of the maximum perpendicular thickness of the vane.

9. A method for designing vanes for the variable geometry turbine of claim 1, the method comprising: selecting a thickness distribution of the vanes to provide a rapid reduction in vane thickness between the leading and trailing edges.

10. The method of claim 9 further comprising: selecting an angular distribution of the vanes wherein the angular distribution is more tangential at the leading edge than at the trailing edge.

11. A variable geometry turbine comprising:

- a turbine housing defining an inlet and an outlet;
 - a turbine wheel rotatably mounted in the turbine housing between the inlet and the outlet such that the turbine wheel can rotate about an axis;
 - a movable wall member mounted in the housing so as to be movable relative to the housing between at least a first position and a second position, the movable wall member partially defining an inlet passageway between the inlet and the turbine wheel, the inlet passageway being radially outboard of the turbine wheel, a dimension of the inlet passageway being dependent on a position of the movable wall member relative to the housing; and
 - a plurality of vanes extending across the inlet passageway, the vanes being circumferentially spaced;
- wherein in cross section each of the vanes has an elongate shape extending from a leading edge which is closer to the inlet to a trailing edge which is closer to the turbine

wheel and wherein the vanes are arranged so as to produce a double wake variation in a static pressure around a circumference of the turbine wheel.

12. The variable geometry turbine of claim 11 wherein the vanes have a shape at least partially defined by a thickness distribution that exponentially reduces from the leading edge to the trailing edge and having an end treatment at each of the leading and trailing edges.

13. The variable geometry turbine of claim 11 wherein the vanes have a shape at least partially defined by an angular distribution that is more tangential at the leading edge than the trailing edge.

14. A variable geometry turbine comprising:

a turbine housing defining an inlet and an outlet;

a turbine wheel rotatably mounted in the turbine housing between the inlet and the outlet such that the turbine wheel can rotate about an axis;

a movable wall member mounted in the housing so as to be movable relative to the housing between at least a first position and a second position, the movable wall member partially defining an inlet passageway between the inlet and the turbine wheel, the inlet passageway being radially outboard of the turbine wheel, a dimension of the inlet passageway being dependent on a position of the movable wall member relative to the housing; and

a plurality of vanes extending across the inlet passageway, the vanes being circumferentially spaced;

wherein in cross section each of the vanes has an elongate shape extending from a leading edge which is closer to the inlet to a trailing edge which is closer to the turbine wheel and wherein the vanes have a shape at least partially defined by a thickness distribution that exponentially reduces from the leading edge to the trailing edge and having an end treatment at each of the leading and trailing edges.

15. The variable geometry turbine of claim 14 wherein the thickness distribution is the thickness distribution in Table 7.

16. The variable geometry turbine of claim 15 wherein an actual thickness of the vanes, with the end treatment at each of the leading and trailing edges, is the thickness distribution in Table 14.

17. The variable geometry turbine of claim 14 wherein the vanes have a shape at least partially defined by an angular distribution that is more tangential at the leading edge than the trailing edge.

18. The variable geometry turbine of claim 17 wherein the angular distribution is the angular distribution in Table 8.

19. A variable geometry turbine comprising:

a turbine housing defining an inlet and an outlet;

a turbine wheel rotatably mounted in the turbine housing between the inlet and the outlet such that the turbine wheel can rotate about an axis;

a movable wall member mounted in the housing so as to be movable relative to the housing between at least a first position and a second position, the movable wall member partially defining an inlet passageway between the inlet and the turbine wheel, the inlet passageway being radially outboard of the turbine wheel, a dimension of the inlet passageway being dependent on a position of the movable wall member relative to the housing; and

a plurality of vanes extending across the inlet passageway, the vanes being circumferentially spaced;

wherein in cross section each of the vanes has an elongate shape extending from a leading edge which is closer to the inlet to a trailing edge which is closer to the turbine wheel, and wherein the vanes have a shape defined by the curves in Tables 9, 10, 11 and 12 multiplied by a scale factor.

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